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E. R. G. Eckert, R. J. Goldstein, M. Y. Jabbari,
S. V. Patankar and T. W. Simon

Co-Principal Investigators

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E.R. Eckert, R. J. Goldstein, M. Y. Jabbari, S. V. Patankar, T. W. Simon

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Minnesota
125 Mechanical Engineering
111 Church Street
Minnesota, MN 55455-0111

8. PERFORMING ORGANIZATION REPORT NUMBER

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The research project finds a number of innovative features. They include: (a) detailed local heat (mass) transfer measurements on turbine blade surfaces, (b) investigation of the mass transfer and turbulent characteristics in curved channel flows, (c) determination of local film cooling effectiveness in endwall film cooling and total-coverage discrete hole wall cooling, (d) evaluation of a fence for endwall flow control, and (e) accurate numerical modeling in film cooling.

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OVERVIEW

The following report documents the accomplishments made toward the understanding of the fluid flow and heat transfer processes within gas turbines. It is a final report (the period from July 1, 1991 to June 30, 1994) under contract number AF/AFOSR-91-0322. Papers which present major findings from the Heat Transfer Laboratory on gas turbine heat transfer are listed in Appendix A. This list is restricted to papers published during and later than 1989. Progress reports, proposals and abstracts which have given details of the work in progress, for their respective periods, are listed in Appendix B. Recent publications are attached and listed in Appendix C. This submittal emphasizes the accomplishments since July 1, 1991.

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1. Turbine Cascade Studies

1.1 Surface measurements of mass (Heat) transfer on gas turbine blades

In recent years, experimental studies of convective transport phenomena on a blade cascade have been conducted in the Heat Transfer Laboratory using the naphthalene sublimation technique. The naphthalene technique is well established and the measurement technique has been developed in the Laboratory. A microcomputer-controlled four-axis (XYZΘ) data acquisition system is used to obtain data on the model turbine blades. The convective transport mechanism on the suction surface was investigated by Chen and Goldstein (1992) and the continuing effort on this subject has been given by Goldstein, Wang and Jabbari (1994). Early related work using the naphthalene sublimation technique includes research on a turbine blade endwall (Goldstein and Spores, 1988).

A new facility for flow visualization and experimental mass transfer tests on gas turbine airfoils and passages has been built (Fig. 1). The facility is designed to easily conduct flow visualization and mass transfer tests for variable-inlet flow conditions which simulate the actual operating conditions in a turbine cascade. The cascade facility includes four first stage blades in a central passage arrangement, two flexible sidewalls, and two tailboards which can be adjusted to produce the correct pressure distribution in the central passage. The blade shape is a high-performance profile. Reynolds numbers based on the exit velocity and blade chord length of up to 500,000 can be reached with this facility. The undisturbed free-stream turbulence intensity of the tunnel is less than 0.2 %. The test apparatus is flexible and can accommodate changes in inlet flow conditions and blade profile.

The facility allows each of the flow characteristics to be examined individually or in combination with other characteristics. Two tailboards trailing the outermost blades, and two flexible bleeds outside the outermost blades are used to adjust the flow within the three turbine passages. The flow is balanced by comparing pressure measurements, made using a special pressure measurement blade, on the surfaces of blades 2 and 3 with each other (an example of which is shown in Fig. 2) and with a potential flow calculation. Figure 1 also shows two interchangeable sections upstream of the cascade; a straight duct section and a grid duct section. The grid duct section has two slots for turbulence grids.

Figure 3 shows a surface flow visualization on the endwall of the central passage using an oil and lampblack method (low turbulence level flow; ~0.2%), as an example. The traces of shear force on the endwall indicate three divided regions which are induced by secondary vortices. This pattern results from two legs of a horseshoe vortex, a passage vortex, two corner vortices, and endwall crossflow (from pressure side to suction side) as shown in Fig. 4. The surface flow pattern is quite different from the results of the old cascade blades (GE CF6-50 model; Jabbari, Goldstein, Marston, and Eckert, 1993). For a high turbulence intensity flow (~8%) elevated by turbulence grids, the surface flow changes in the front part of the passage possibly due to unsteadiness of the several vortices. The result indicates that the endwall is divided to two different flow regions (Fig. 5).

An extensive smoke-wire flow visualization study has been conducted and video taped with the aid of a laser light sheet (Wang, Olson, Goldstein, and Eckert, 1995). Eight tungsten wires were positioned horizontally ahead of the cascade near the endwall. Four sets of video tape have been produced that follow the vortex flow pattern from different visual angles. Figures 6 and 7 show examples of the smoke-wire flow visualization results. According to the spatial and surface flow visualization, a new flow model is formulated (Fig. 4). The major feature of the secondary flow pattern is that the new vortex (V_{wip}) induced by the passage vortex has a significant effect on heat transfer from the suction surface which can be clearly seen in naphthalene experiments. The suction leg of the horseshoe vortex has little effect on the blade surface, except near the leading edge. It wraps itself around the passage vortex as it travels along the passage, becoming a small portion of the passage vortex.

The primary purpose of the study which utilizes this facility is to obtain local heat (mass) transfer coefficients on turbine blade surfaces. The mass transfer test blade is of a similar design to that used in our earlier investigations (Chen and Goldstein, 1992) and allows the measurements of approximately 2000 discrete measurement points on the two surfaces. Information on the detailed local heat transfer coefficients is essential in understanding heat transfer characteristics in turbine passages and predicting regions of excessive surface temperature as a result of separation or transition. This information can be used to analyze thermal stress distributions on the blade, to evaluate the effects of the inlet flow conditions on heat transfer and to assist in blade design, from a heat transfer perspective. The detailed information is also useful in the development of numerical models for heat transfer analysis on gas turbine surfaces.

1.2 Analysis of Flow within a Highly-loaded Turbine Stage

A two-half-airfoil cascade simulator was developed to model a highly-loaded gas turbine fluid mechanical environment in the free stream and pressure and suction surface boundary layers over the two-dimensional flow region (Smith, 1993). Variation of static pressure along both the suction and pressure walls (Fig. 8) was examined to gain an understanding of the how the boundary layers developed. The total pressure variation at the channel exit (Fig. 9) was examined for evidence of cross transport of momentum from the suction wall to the pressure wall, as observed in the curved channel. In Fig. 9, near the concave wall, ($0.05<y/c<0.3$), cross-stream transport was found to lead to an increase of momentum ($y/c\approx0.07$) at the expense of momentum nearer the convex wall ($y/c\approx0.25$).

To expand upon the gas turbine simulator data, the PCPANEL computer program was used to investigate the sensitivity of the pressure profile to the attack angle (Wang, 1995) for the geometry of the two-half-blade cascade simulator used in the experiment. The program, developed at NASA Lewis Research Center, was used to simulate the flow and compute the velocity and pressure distributions. The pressure profile at 35° attack angle matched experimental results quite well. The distribution of the acceleration parameter, K, was calculated from the velocity distribution and it was demonstrated that this profile, cast in terms of $K\cdot \mathrm{Re}_c$, is independent of Re_c (Figs. 10 and 11).

1.3 An Investigation of the End-wall Flow

An experimental investigation of the three-dimensional flow and heat transfer near the junction between the end-wall and suction wall of a gas turbine was conducted (Chung, 1992). A large-scale, two-half-blade facility was constructed to do this (Chung and Simon, 1990). Various flow visualization techniques, static pressure measurements, and laser-Doppler velocimetry were employed to confirm that a cascade flow was replicated. Experimental results showed that the secondary flow, including the passage vortex, was visible in both the low-free-stream-turbulence case and another case with an entrance turbulence level of about 10% (Chung, 1992). Some details of this flow changed, however, due to stronger diffusion with increased turbulence.

The effectiveness of a boundary layer fence was also documented. The fence decreased the aerodynamic loss within the channel flow and increased the potential to improve film cooling performance in a gas turbine (Chung and Simon, 1993). Though no film cooling data were taken, it was shown that the fence can change the path of the horseshoe vortex and reduce the influence of the vortex on the flow near the suction wall, even with the high free-stream turbulence level. This suggests that film cooling performance may also be improved by the presence of the fence. The area near the endwall, which is influenced by secondary flow, has higher heat transfer coefficients than values measured in the two-dimensional region away from the endwall. The fence is even more effective in reducing the secondary flow for the high turbulence case than for a low-TI case (Fig. 12). This reduction in secondary flow activity includes the region on the suction surface where secondary flow is known to augment heat transfer coefficients (Figs. 13 and 14). On Fig. 14, total loss, which is equal to the drop in the total pressure plus the secondary flow (swirl) velocity head,

$$C_{total} = \frac{2(P_{t_\tau} - P_t) + V^2 + W^2}{U_o^2},$$

is plotted. The velocity head was added because such velocity was considered unrecoverable. The fence reduced this loss for it prevented the pressure side leg of the horseshoe vortex from crossing to the suction surface at full strength and impinging on the wall (Chung and Simon, 1991). Turning the vortex to align it with the main flow prevented the vortex from gaining full strength.

2. Flow and Heat Transfer in a Curved Channel

2.1 Mass transfer downstream of 90° bend

The effects of the corner vortices on mass transfer in a straight square duct was discussed by Goldstein, Jabbari, and Brekke (1992). The experimental condition tested was a nearly fully developed duct flow and a developing mass transfer boundary layer; a condition often encountered in the internal cooling channels of a turbine blade. In a continued study, the mass (heat) transfer downstream of a 90° bend in a square duct is investigated using the naphthalene sublimation technique. The flow is turbulent in all cases: Reynolds numbers of 15000 to 50000 are investigated, corresponding to Dean numbers of 6960 to 23190. The average mass transfer downstream of the bend is greater than the average mass transfer in a straight duct. However, at some locations in the duct cross section, the local mass transfer is actually less than the corresponding local mass transfer in a straight duct.

The mass transfer distributions on the inner, bottom, and outer walls differ greatly in pattern. Figure 15 shows contour plots of the mass transfer on the walls. A small effect on the mass transfer of the stress driven secondary flows characteristic of turbulent flow in a rectangular channel is detected. There is some evidence to suggest that the mass transfer in the test section is influenced most by the bend at the lowest Reynolds number. The complete results of these investigations are contained in Burns (1991) and will be published in the near future.

2.2 Effects of Streamwise Curvature on Turbulent Boundary Layer Flows

Experiments were performed to investigate the behavior of boundary layers on curved walls of sustained concave curvature and flat walls downstream (Kestoras, 1993). The experiments were conducted with a negligible streamwise pressure gradient and at both a low free-stream turbulence intensity (0.6%) and a high free-stream turbulence intensity of 8%. The turbulent boundary layer had a moderate strength of curvature ($\delta / R = 0.024$) at the entry to the recovery section.

Low Free-Stream Turbulence

Experimental results at low free-stream turbulence intensity on a flat wall showed that the skin friction coefficient increased over the concave wall, then

decreased rapidly at first over the flat recovery wall, followed by a slow approach to flat-wall values (Kestoras and Simon, 1992 and Kestoras, 1993). A pattern of Görtler streamwise vortex cells (Fig. 16) formed on the concave wall. On the recovery wall, Stanton number values decreased rapidly, undershooting expected flat-wall values. Overall, for the recovery wall, turbulent transport of momentum and heat were substantially lower than comparable data taken over a flat-wall boundary layer (Kestoras and Simon, 1994b and Kestoras, 1993). The cross-stream transport of heat ($\overline{v't'}$) and momentum ($\overline{u'v'}$) behaved similarly over both the curved wall and the flat recovery wall across most of the thickness of the boundary layer. As with the other quantities, streamwise heat flux values dropped abruptly at the exit of the bend and were slow to recover.

High Free-Stream Turbulence

In contrast to the low-free stream turbulence intensity flow, boundary layer turbulence intensity values were elevated profoundly in the outer region of the boundary layer for the elevated free-stream turbulence case and high levels of transport of momentum and heat were measured over the concave surface, even outside of the boundary layer (Kestoras and Simon, 1993b). Skin friction coefficients and Stanton number values on the recovery flat wall were 20% and 10%, respectively, above their counterpart values from the low-free stream turbulence intensity case. On the curved wall, stationary, Görtler-like vortices, observed under low-TI conditions did not form and skin friction coefficient values for the high-turbulence case increased about 2% above spanwise-averaged values of the low-TI case (Kestoras and Simon, 1994a). Turbulent Prandtl numbers within the log region of the boundary layer over the concave wall increased with streamwise distance to values of as high as 1.2. Stanton numbers did not undershoot the flat-wall expected values (for the same Re_{Δ_2}) as seen in the low-TI case (Kestoras and Simon, 1993b). Stanton numbers showed very little increase with streamwise distance on the upstream part of the concave wall but remained about 5% above the low-TI values (Kestoras and Simon, 1993a).

Turbulent transport quantities such as $-\overline{u'v'}$ and $\overline{v't'}$ were significantly enhanced in the elevated free-stream turbulence case (Figs. 17 - 19) in most of the outer part of the boundary layer (Kestoras and Simon, 1994a and Kestoras and Simon, 1995). On the flat, recovery wall, it appeared that near-wall turbulent eddies lifted off the recovery wall and a "stabilized" region formed near the wall. Near-wall values of $\overline{v't'}$ over the recovery wall were unaffected when free-stream turbulence intensity was elevated. Other results showed that

turbulent Prandtl number, P_{r_t}, values over the recovery wall were reduced to 0.9 when free-stream turbulence intensity was elevated (Kestoras and Simon, 1993b). The velocity distribution in the core of the flow over the flat recovery wall exhibited a negative gradient normal to the wall under high free-stream turbulence intensity conditions (Kestoras and Simon, 1993b). This was explained in terms of cross-transport by boundary work. On the curved wall, the cross transport of momentum, which raised the stagnation pressure near the concave wall, was active both within and outside the boundary layer, creating more shallow gradients of velocity than those which would exist in a potential flow (Kestoras and Simon, 1993a). When curvature was removed and the static pressures readjusted, the remains of this cross-transport was visible as a higher velocity near the concave wall.

3. Film Cooling Studies

3.1 Endwall film cooling of gas turbine blades

Film cooling performance with injection through holes and a slot in the endwall of a turbine blade passage has been investigated. Film cooling of the endwall of gas turbine passages has recently become important with the increase of gas turbine inlet temperatures. The endwall film cooling pattern is strongly affected by the turbine passage fluid mechanics. Its main features are a strong endwall secondary flow driven by the acceleration of boundary layer fluid from the pressure surface to the suction surface. Another important feature is a large horseshoe vortex formed at the junction between the airfoil leading edge and the endwall. Moreover, pressure distribution on the endwall controls flow rate of the coolant through individual holes. Thus, it is difficult to predict the film cooling effectiveness on the endwall due to these complex flow patterns.

In the present studies (Marston, 1991, and Jabbari, Marston, Eckert, and Goldstein, 1994), the endwall between two modern gas turbine blades is provided with 21 injection holes. The blades are installed in a plane cascade. The film cooling effectiveness is measured through the heat-mass transfer analogy. For this purpose, 85 sampling taps are drilled through the endplate. Air and Helium or air and Sulfur-Hexafluoride (SF_6) mixture are used as a secondary gas which provides a wide range of density ratios between mainflow and the secondary gas flow. The results of the study provide the desired effectiveness values at the 85 sampling taps. However, the variation is so strong that even 85 measurement points are not sufficient for determining the total field of film cooling effectiveness over the endwall surface.

Flow visualization, in which ammonia and water vapor are added to the secondary air, is conducted on the endwall. The endwall is covered by Diazo paper which changes color wherever it comes into contact with the ammonia in the jets. Figure 20 is an example of the visualization obtained in this way. It is found that the directions of the jets indicated by this visualization coincide well with the mainstream flow direction at a slight distance from the wall (outside the boundary layer). The nonuniform distributions of effectiveness values on the endwall are indicated by mass transfer measurements and flow visualization. To improve the film cooling performance, cooling air ejection through a slot, which may be provided by the joints between adjacent blades, is conducted on the endwall (Thor, 1993). The benefit of slot injection is shown

in Fig. 21 which is obtained by secondary gas injection through both a slot and holes (the area which experiences the largest benefit is the downstream region). Note that the injection hole position and angle are changed from the previous experiment. Generally, the combination of holes and slot have much higher effectiveness than the holes or the slot injection alone. The results of these investigations will be published in the near future.

3.2 Total-coverage discrete hole wall film cooling

Investigations of total coverage film cooling have been conducted to improve the cooling performance on a gas turbine blade (Cho and Goldstein, 1995). For this cooling scheme, heat transfer coefficients and film cooling effectiveness values on the region near the injection holes are important. In heat transfer experiments, it is difficult to determine the local values in these regions due to conduction errors and sharp temperature gradients. Thus, a mass transfer technique (i.e. naphthalene sublimation technique) has been used to measure the local cooling effectiveness values and transfer coefficients on inside hole surfaces and internal walls as well as on exposed surfaces (near injection holes). In the present study, two sets of experiments are conducted to determine both the cooling effectiveness and the transfer coefficient. First, pure air is injected as a secondary flow and secondly saturated naphthalene vapor in air is injected as a secondary flow. These experiments provide all the information required to analyze overall heat transfer fluxes around holes. This report presents the results obtained on the injection holes as shown in Fig. 22 (Cho and Goldstein, 1993).

Figure 23 shows the heat/mass transfer coefficients on the inside hole surface for various blowing rates. The size of the recirculation zone increases with the blowing rate and reaches the same size as in the case without cross-flow at high blowing rates because the jet at the high blowing rate has more momentum and is less affected by the cross-flow. High mass transfer rates are shown on the reattachment region because the flow essentially impinges on the wall. The level of the peak Sh value is about the same as without cross-flow, except at a low blowing rate, $M = 0.22$. After reattachment, the boundary layers of flow and mass develop and the mass transfer rates decrease slowly at approximately the same rate as those without cross-flow. In this region, the mass transfer rate is affected weakly by the cross-flow. On the region near the exit of the hole, the cross-flow pushes the jet toward the downstream edge of the hole and this detaches the jet from the leading edge of the hole. The mass

transfer rates increase on this region because the developing vortex by cross-flow disturbs and interacts with the jet flow. However, this directly affected region is confined to near the exit of the injection hole which is about $0.15D_h$ in depth. This is very different from the case without injection (e.g., the case of a clogged injection hole) for which the entire hole area is affected (Fig. 24). This implies that the inside of the hole will be damaged greatly by mainstream for no injection but can be protected from the mainstream with even a low blowing rate.

Convective heat/mass transfer near and within the entrance region of film cooling holes supplied with air from an internal duct (plenum) behind the cooling holes has been investigated by Goldstein, Cho, and Jabbari (1994). The mass transfer of the cross-flow entering the hole is inferred from the combination of flow along a 90° tube bend and a sudden contraction duct flow. The mass transfer coefficients for the duct wall with a cooling hole are three to five times higher than for a fully developed duct flow (Fig. 25).

4. Computational Study of Film Cooling

Professor Patankar and co-workers have been active in the development of numerical methods and mathematical models and their application to a variety of practical situations. The studies that are directly relevant to turbine blade heat transfer and film cooling are outlined here.

The heat transfer on a gas turbine blade is strongly influenced by free-stream turbulence, which controls the transition from laminar to turbulent flow. Figures 26 and 27 show the results of Schmidt and Patankar (1991a, 1991b) for heat transfer along the blade surface for different free-stream turbulence levels. The numerical predictions are shown by solid lines and are compared with experimental data shown by the symbols. It can be seen that the turbulence model used in the computations is correctly able to predict transition as influenced by free-stream turbulence.

Whereas streamwise injection is the more common mode of film cooling, lateral injection has been found to give a more uniform film-cooling effectiveness. The reason lies in the cross-stream velocity patterns that are produced in the two types of injection. The streamwise injection tends to lift the coolant jet away from the wall and, in turn, brings the mainstream hot fluid in contact with the wall; on the other hand, lateral injection produces a continuous blanket of cold fluid on the blade surface. This can be seen in Fig. 28 taken from Sathyamurthy and Patankar (1990), where the cross-stream velocity vectors are shown for the two types of injection. Figure 29 shows the temperature distribution on the blade surface for different angles of lateral injection. The 90-degree lateral injection can be seen to produce a fairly uniform cooling effect over the entire surface.

The anisotropy of turbulence is recognized as a major consideration in the correct prediction of film-cooling, especially for the case of streamwise injection. The use of an isotropic turbulence model does not give sufficient lateral spreading of the film-cooling jet. This is shown in Fig. 30 taken from Sathyamurthy and Patankar (1992), where the cooling effectiveness values are shown for the isotropic and anisotropic turbulence models. Figure 31 shows comparison of predictions with the measurements of Kadotani (1975). The isotropic model overpredicts the effectiveness along the centerline of the hole and underpredicts it along the line midway between two holes. A proper anisotropic correction to the model is able to give a satisfactory agreement with experimental data.

For handling complex geometries, Patankar and co-workers have developed calculation methods employing general curvilinear coordinates (Karki and Patankar, 1988a, 1988b, 1989). These techniques can be used for an accurate solution of the flow in and around the injection holes of different geometries.

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Schmidt, R. and Patankar, S. V., 1991a, "Simulating Boundary Layer Transition with Low-Reynolds-Number k-ε Turbulence Models: Part 1 - An Evaluation of Prediction Characteristics," Journal of Turbomachinery, Vol. 113, pp. 10 - 17.

Schmidt, R. and Patankar, S. V., 1991b, "Simulating Boundary Layer Transition with Low-Reynolds-Number k-ε Turbulence Models: Part 2 - An Approach to Improving the Predictions," Journal of Turbomachinery, Vol. 113, pp. 18 - 26.

Smith, D. J., 1993, "Fluid mechanics measurement in a cascade simulator which models the gas turbine environment", M.S. Thesis, Department of mechanical engineering, University of Minnesota.

Thor, E. J., 1993, "Film Cooling of a Gas Turbine Cascade Endwall with Injection Through Holes and a Slot," M.S. Thesis, Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN.

Wang, H. P., Olson, S. J., Goldstein, R. J., and Eckert, E. R. G., 1995, "Flow Visualization in a Linear Turbine Cascade of High Performance Turbine Blades" to appear in IGTI Conf., Houston, 1995.

Wang, L.,1995, "PCPANEL Code Description in Airfoil," M.S. Thesis, Department of Mechanical Engineering, University of Minnesota.

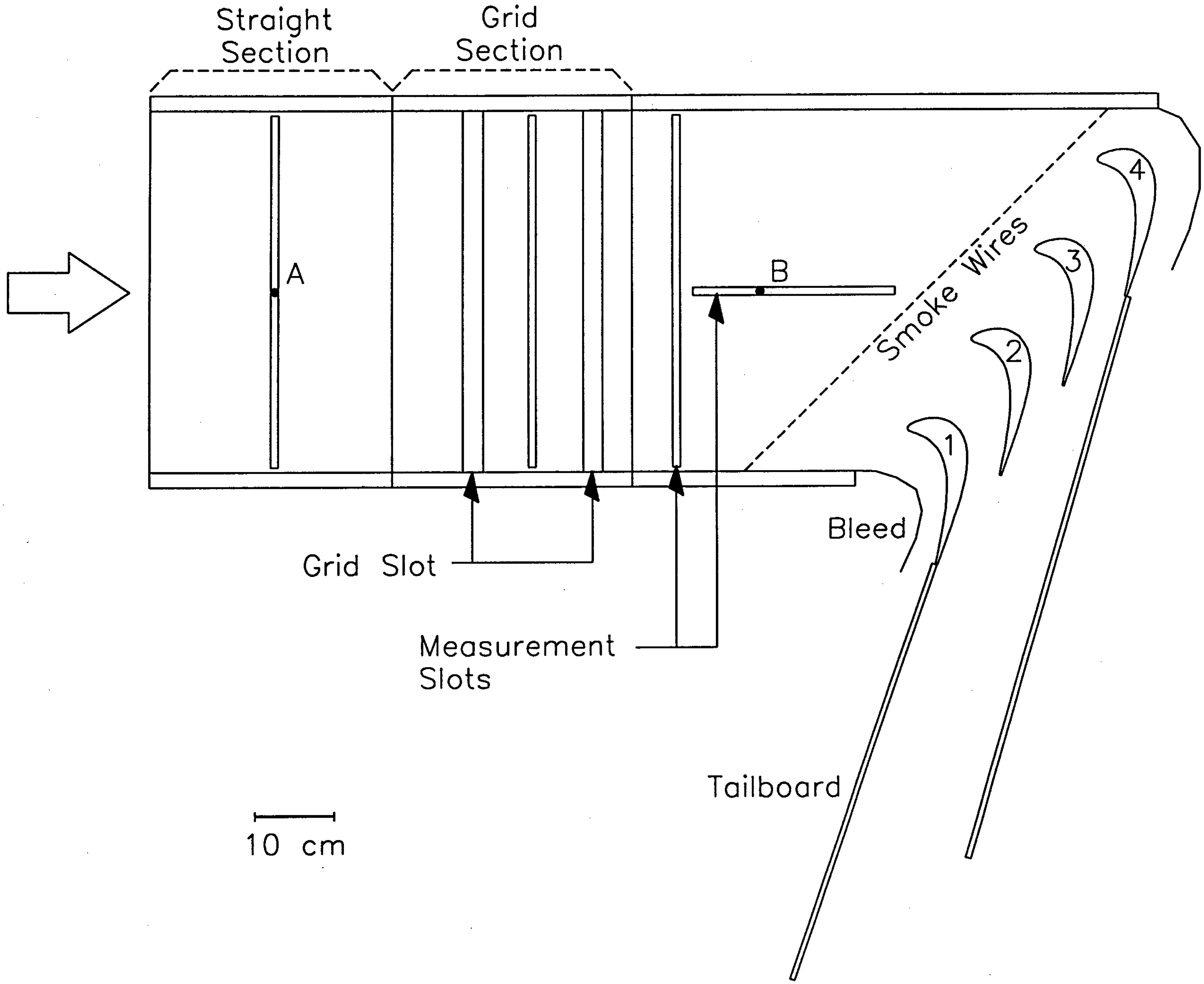

Fig. 1 Top view of new mass transfer cascade showing the layout of the test blades and the tailboard and bleeds used for flow balancing.

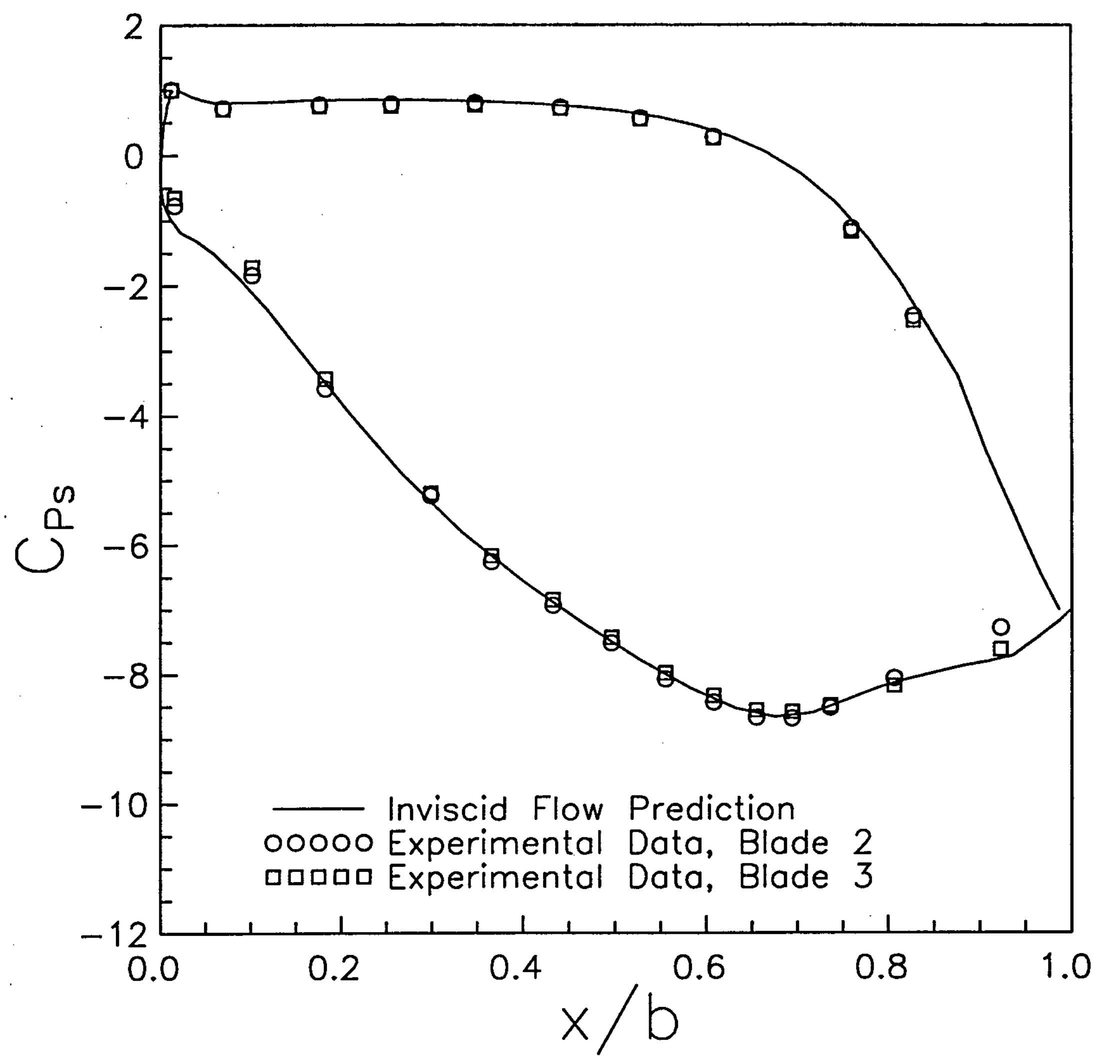

Fig. 2 Experimental pressure distribution on central passage's bounding blades.

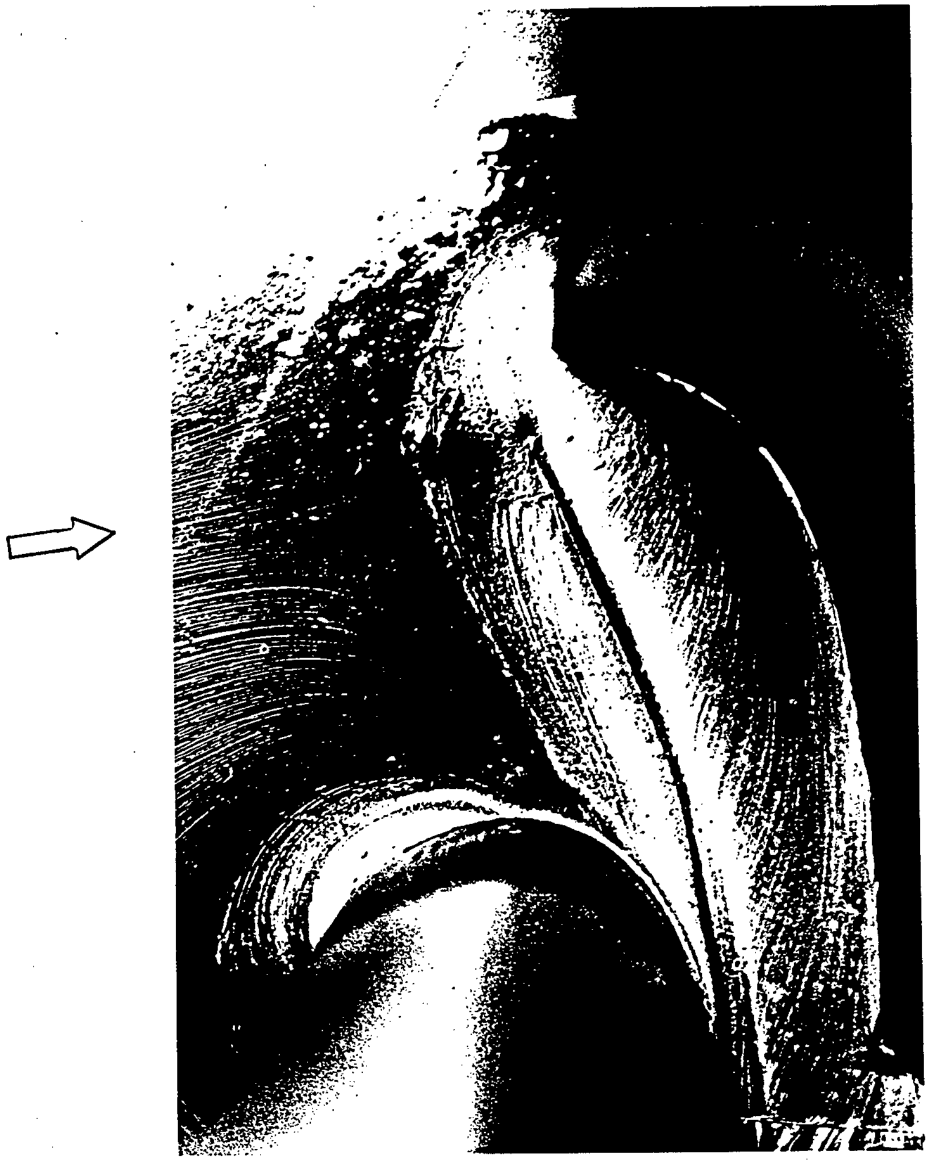

Fig. 3 Oil and lampblack visualization of the endwall (low turbulence intensity; ~ 0.2%).

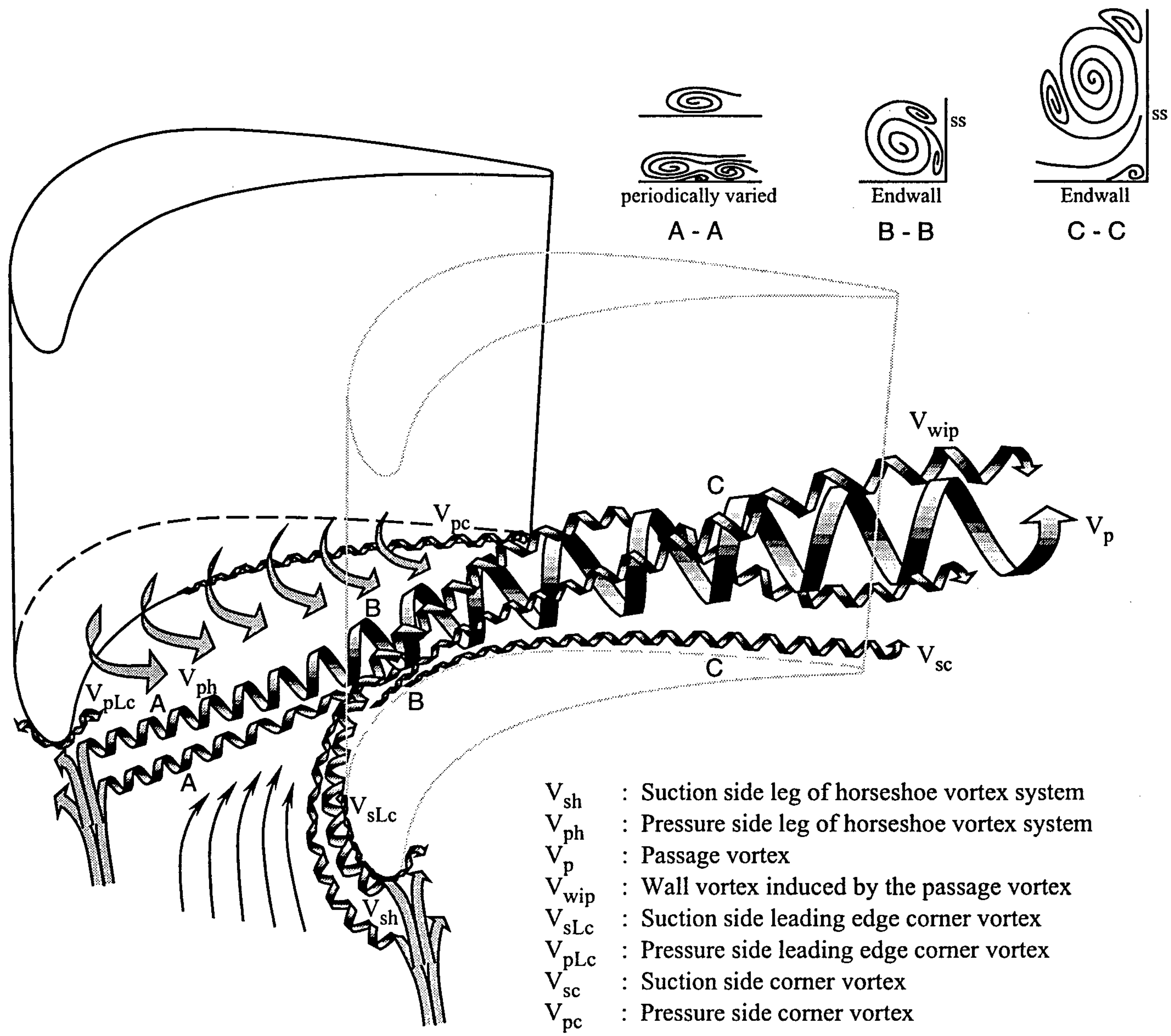

Fig. 4 Diagram of the secondary flow pattern as determined through the surface and smoke wire flow visualization studies.

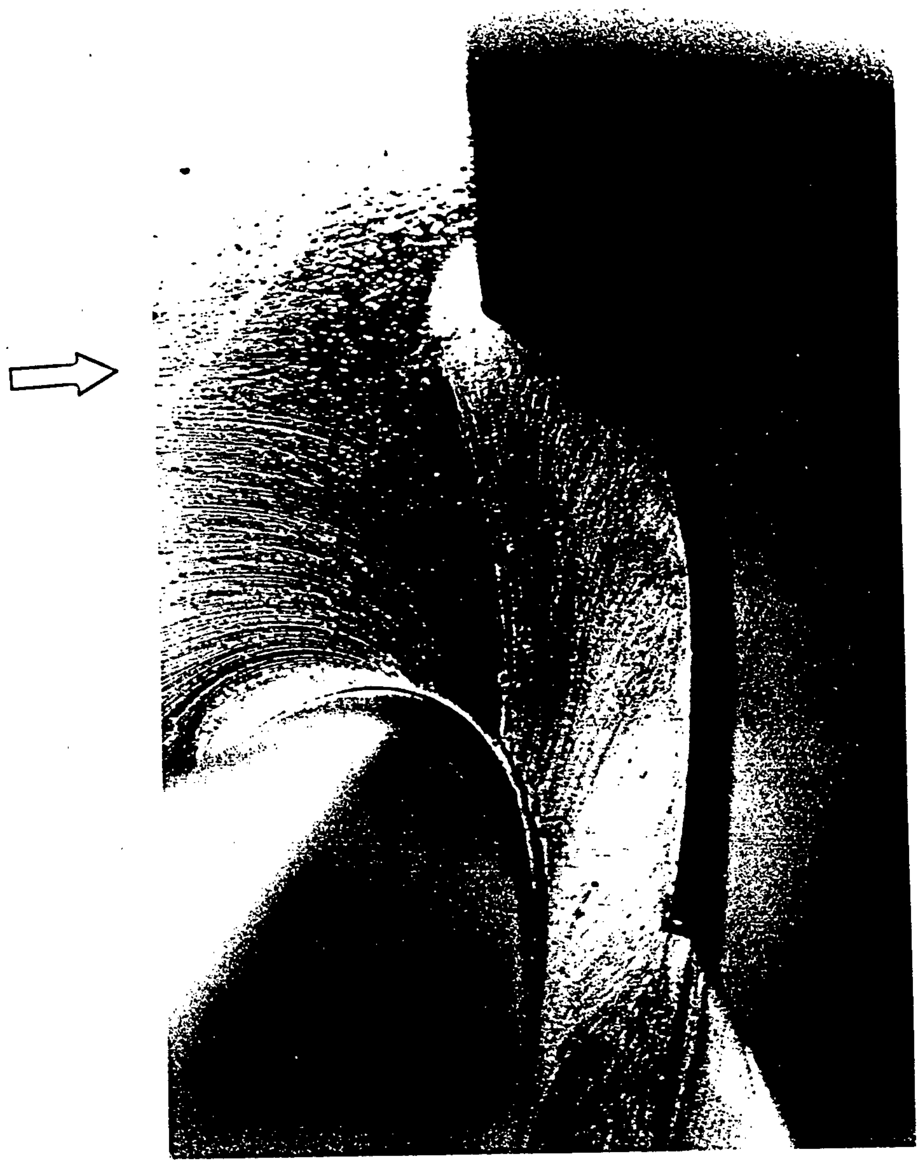

Fig. 5 Oil and lampblack visualization of the endwall (high turbulence intensity; ~ 8%).

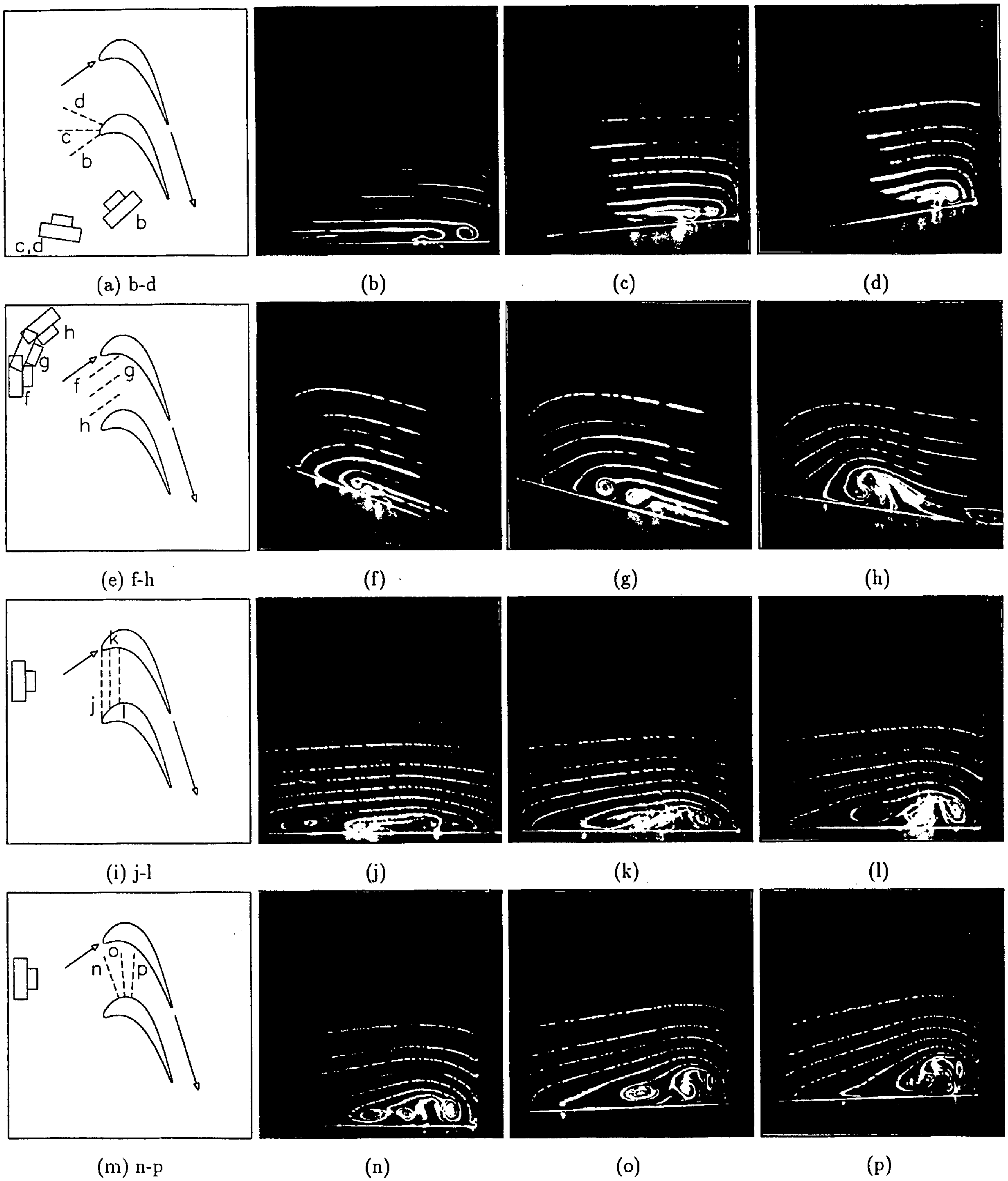

Fig. 6 Smoke wire flow visualization of the flow passage in the new cascade.

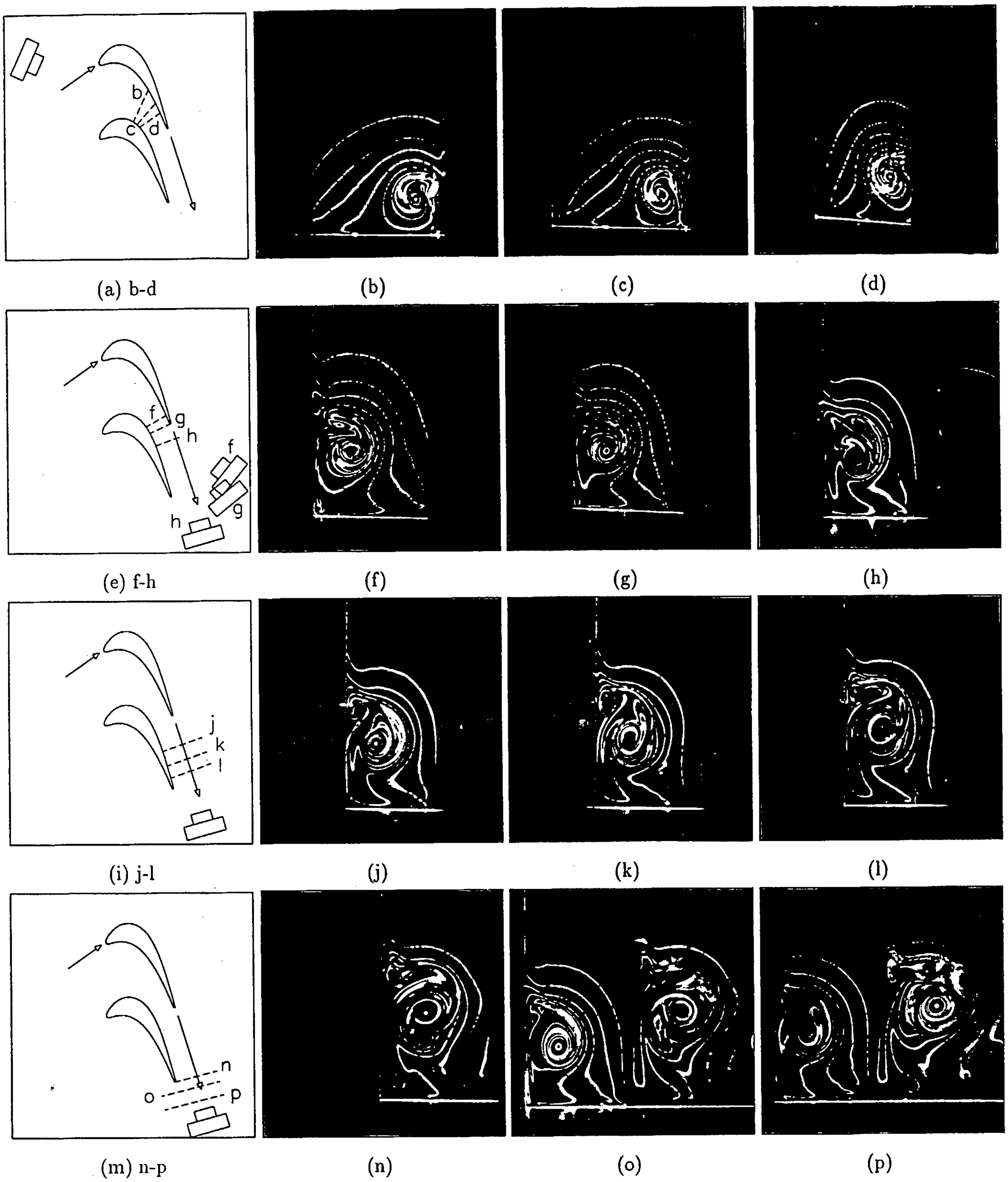

Fig. 7 Smoke wire flow visualization of the flow passage in the new cascade.

Profile of Cp: Adjusted Wall Orientation

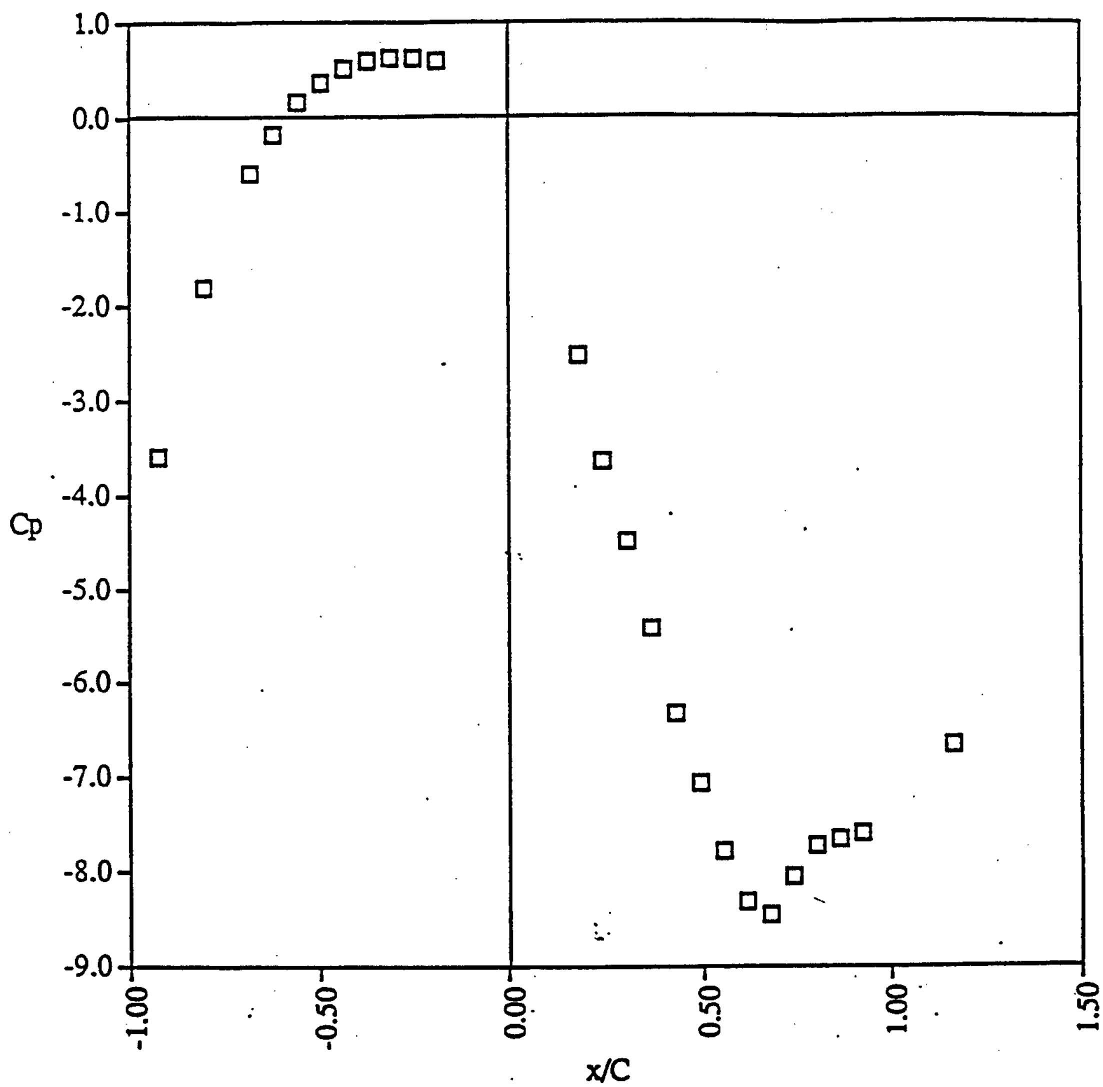

Fig. 8 Cp Profile for Channel Walls

$C_p = {(P - P_{ref})} \Big/ {\tfrac{1}{2}\rho U_1^2}$; U_1 is the approach flow velocity.

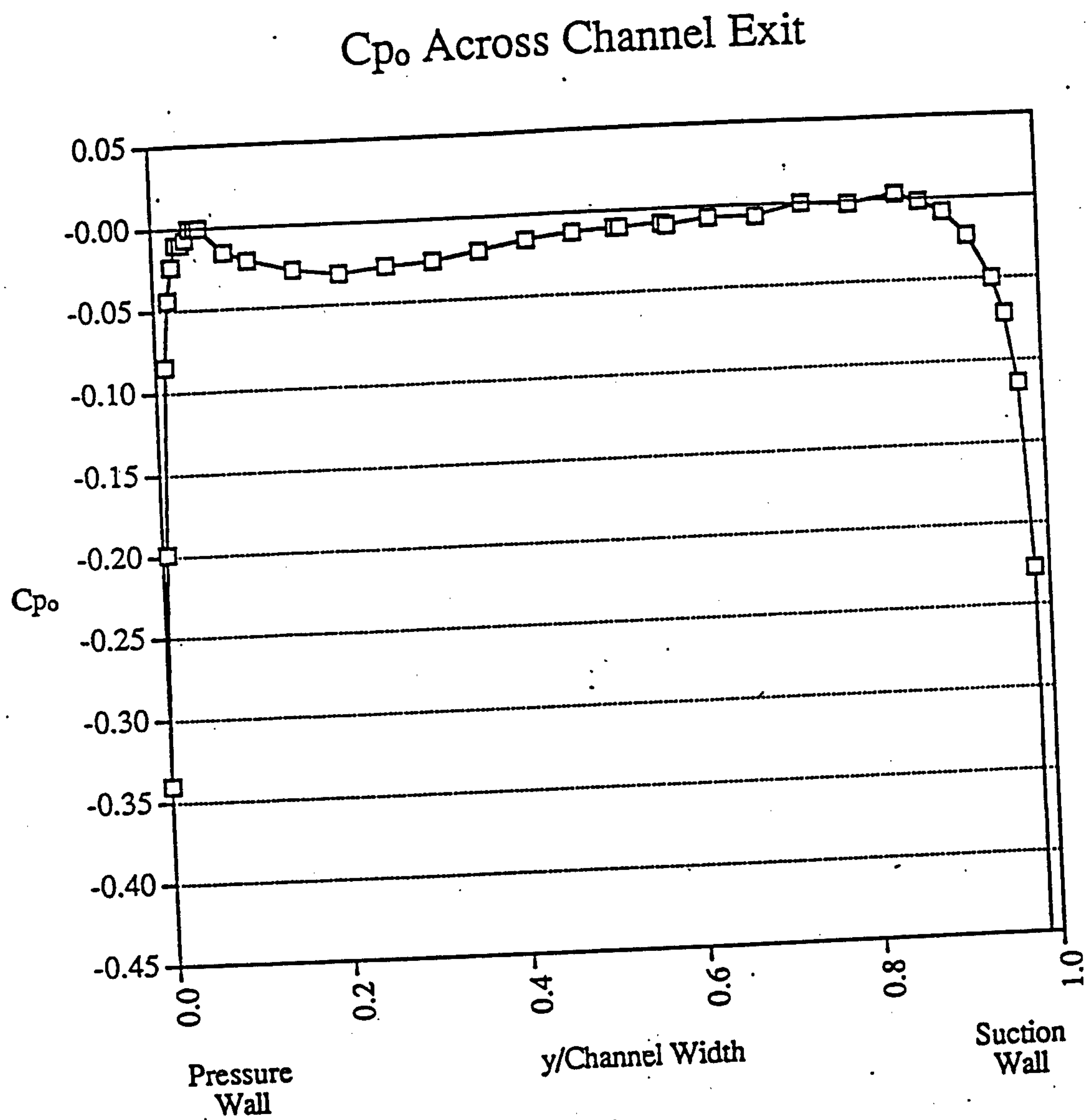

Fig. 9 Cp_o Across the Channel Exit -- Enlarged Vertical Scale

$C_{p_o} = \left(P_{tot} - P_{tot,ref}\right) \Big/ \tfrac{1}{2}\rho U_1^2$; U_1 is the approach flow velocity.

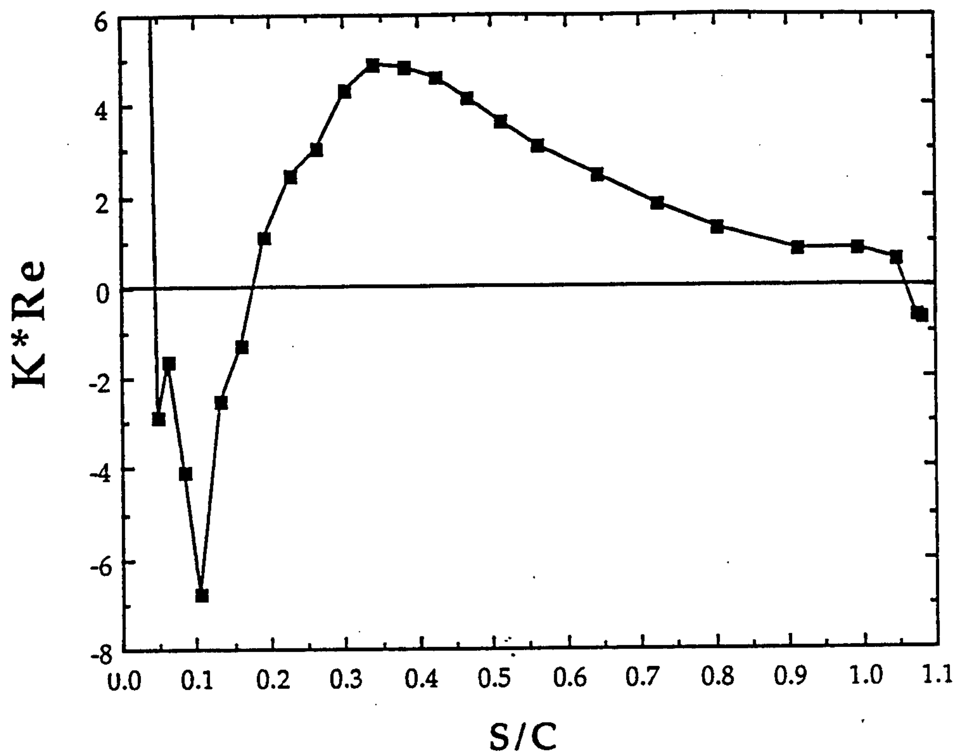

Fig. 10 K*Re_c product distribution along pressure wall side (Re_c=634244 and 186045)

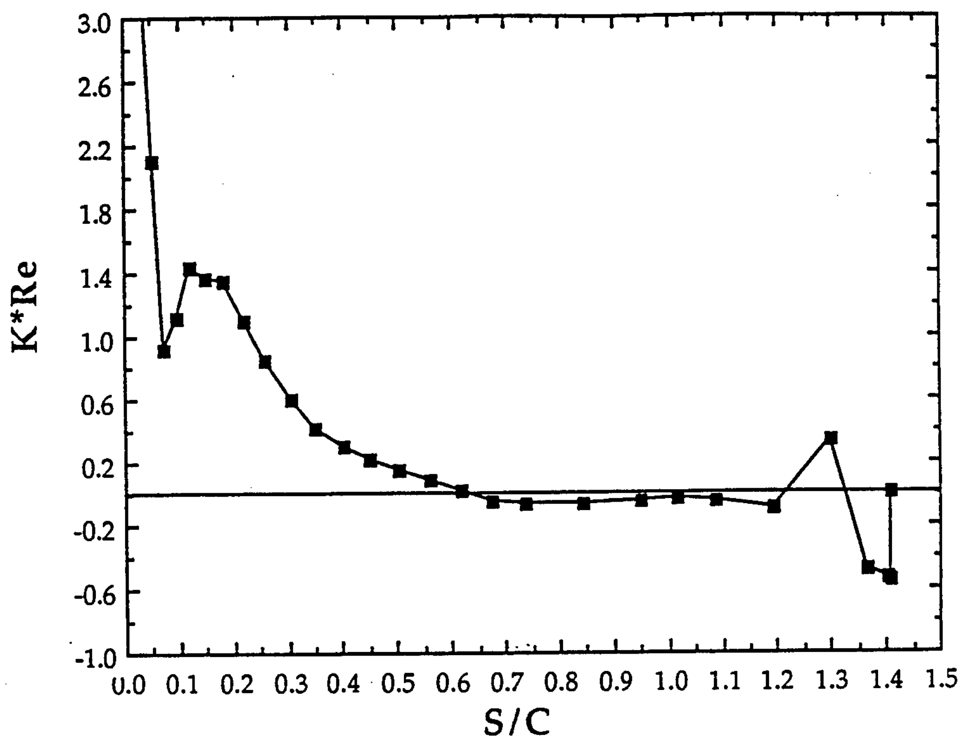

Fig.11 K*Re product distribution along suction wall side (Re=634244 and 186045)

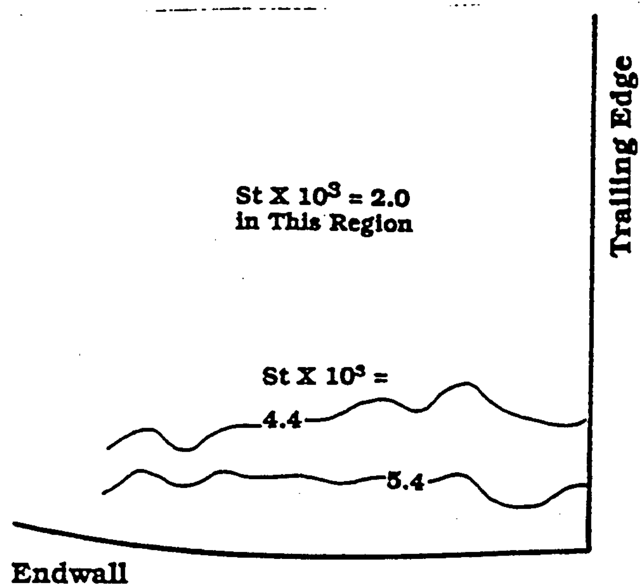

Fig. 12 a Contour of the Stanton number on the suction wall generated from liquid crystal visualization (high TI case)

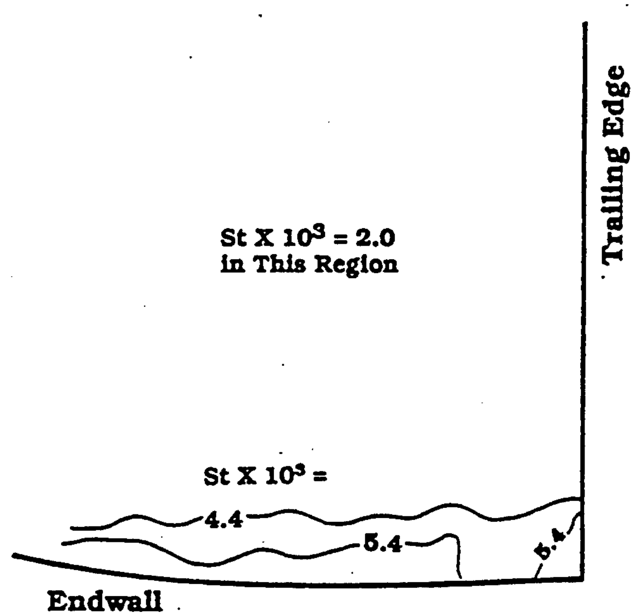

Fig. 12 b Contour of the Stanton number on the suction wall generated from liquid crystal visualization (with fence, high TI case)

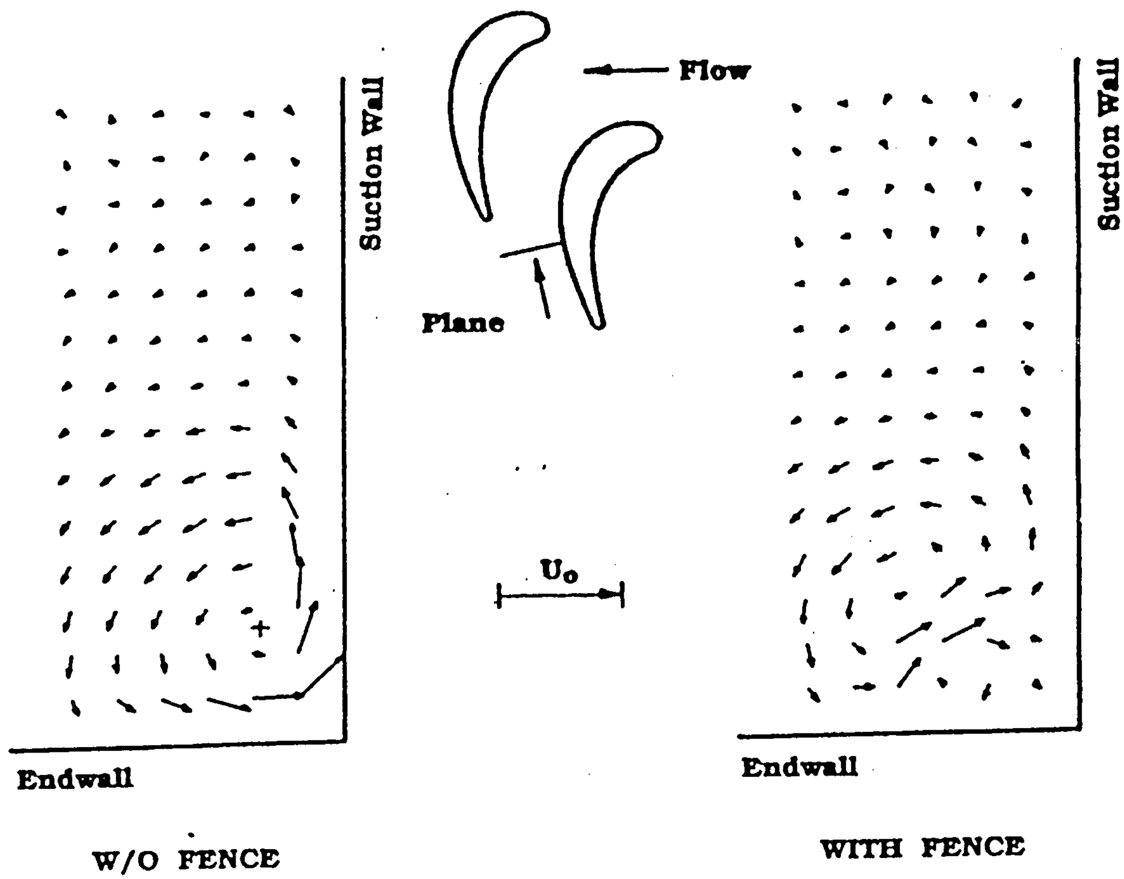

Fig. 13 Secondary Flow Vectors at a Plane (with and without fence).

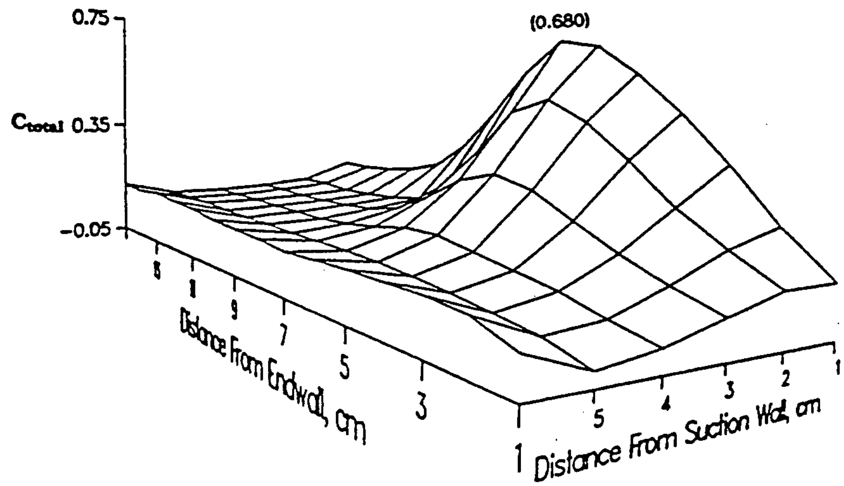

Fig. 14 a Distribution of the Total Loss at a Plane (without fence).

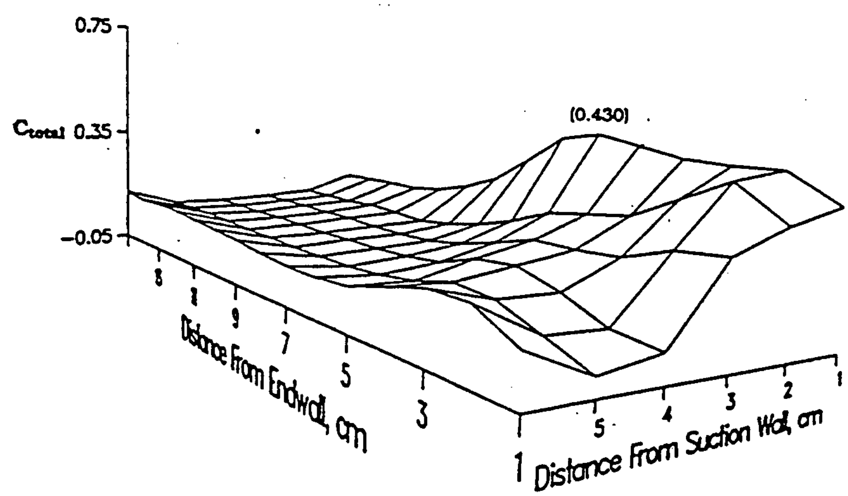

Fig. 14 b Distribution of the Total Loss at the Plane (with fence).

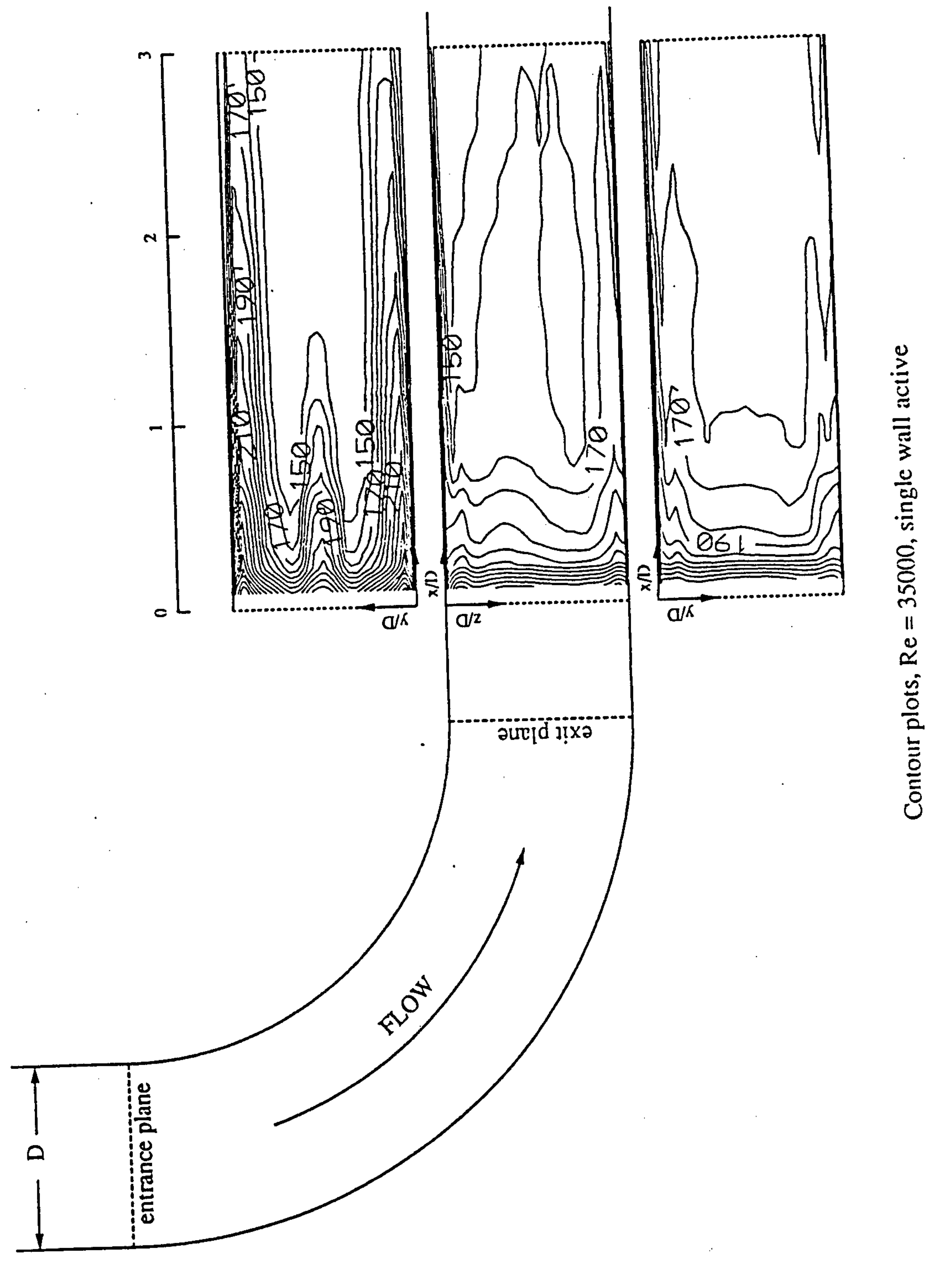

Fig. 15 Mass transfer distribution on the walls downstream of a bend.

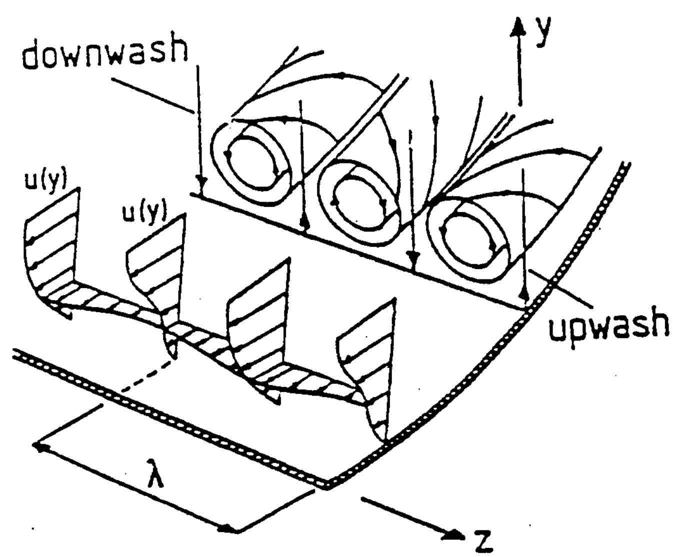

Fig. 16 Schematic of Görtler Vortices (From Crane and Sabzvari, 1984)
For High-TI case, the Structure Was Not Visible.

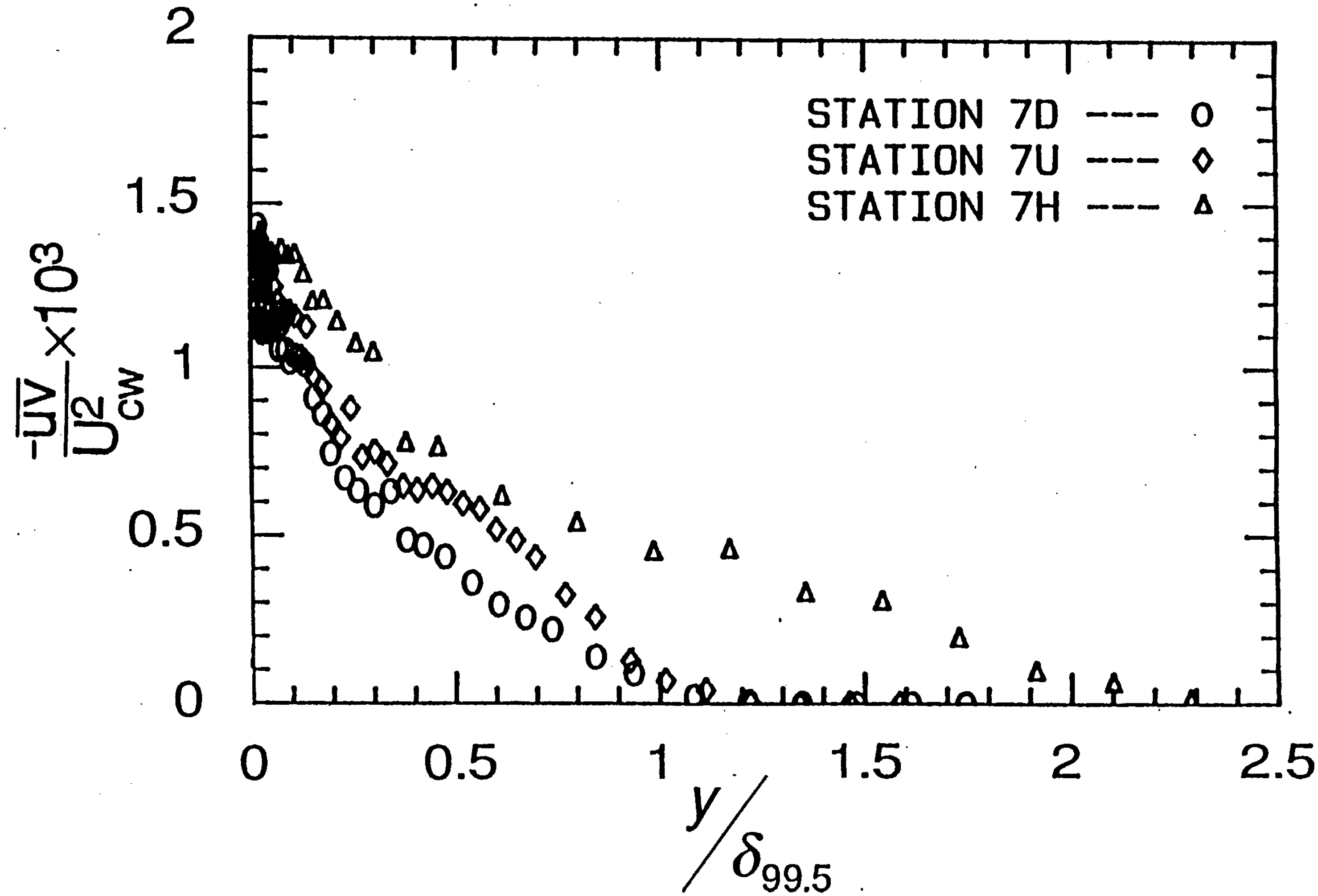

Fig. 17 Effect of Elevated TI on Turbulent Shear Stresses over the Recovery wall, Station 7H--High-TI; Station 7D--Low-TI. D--Downwash, U--Upwash

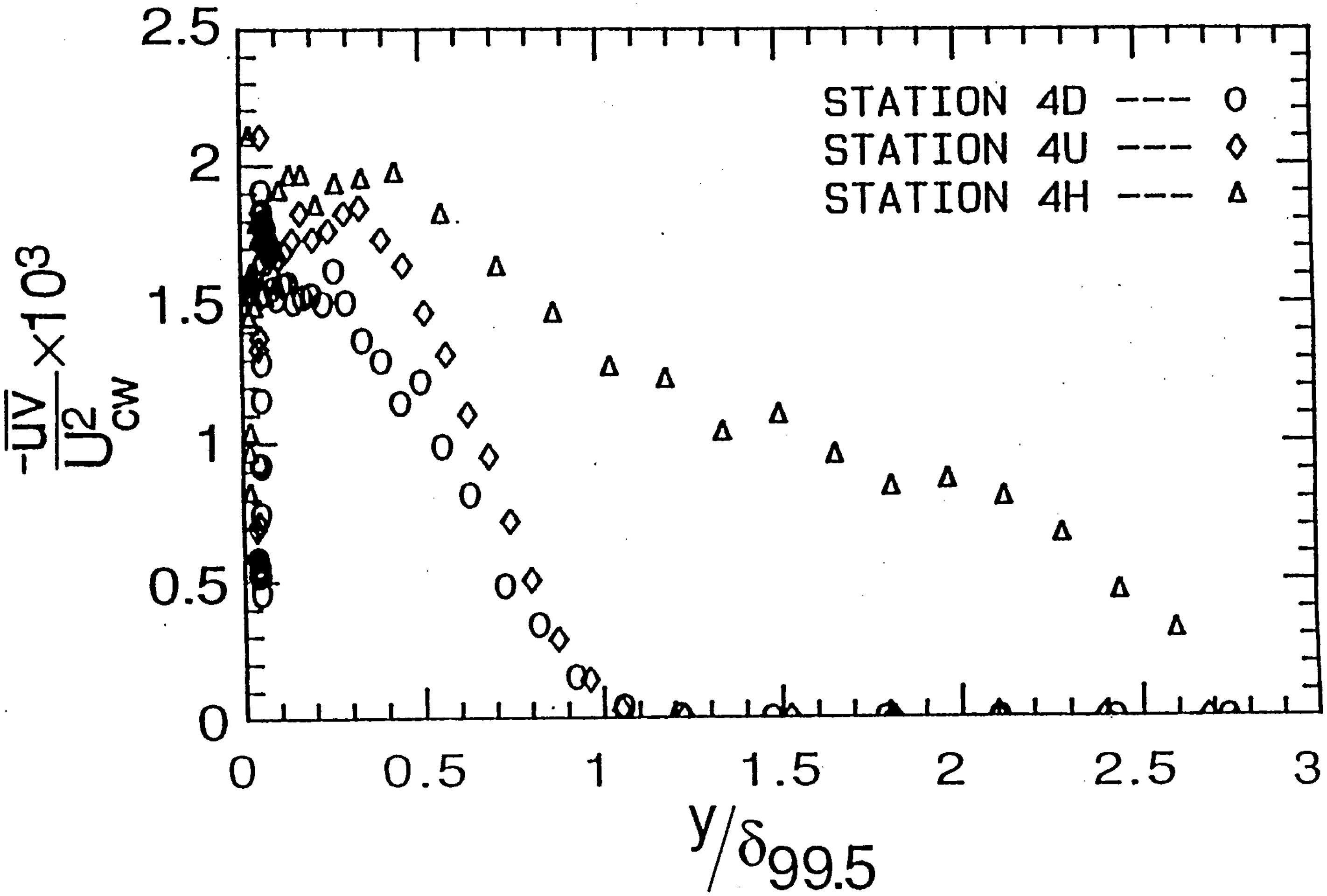

Fig. 18 Effect of Elevated TI on Profile of Turbulent Shear Stresses over the concave wall, Station 4H--High-TI; Station 4D and 4U--Low-TI.
D--Downwash, U--Upwash

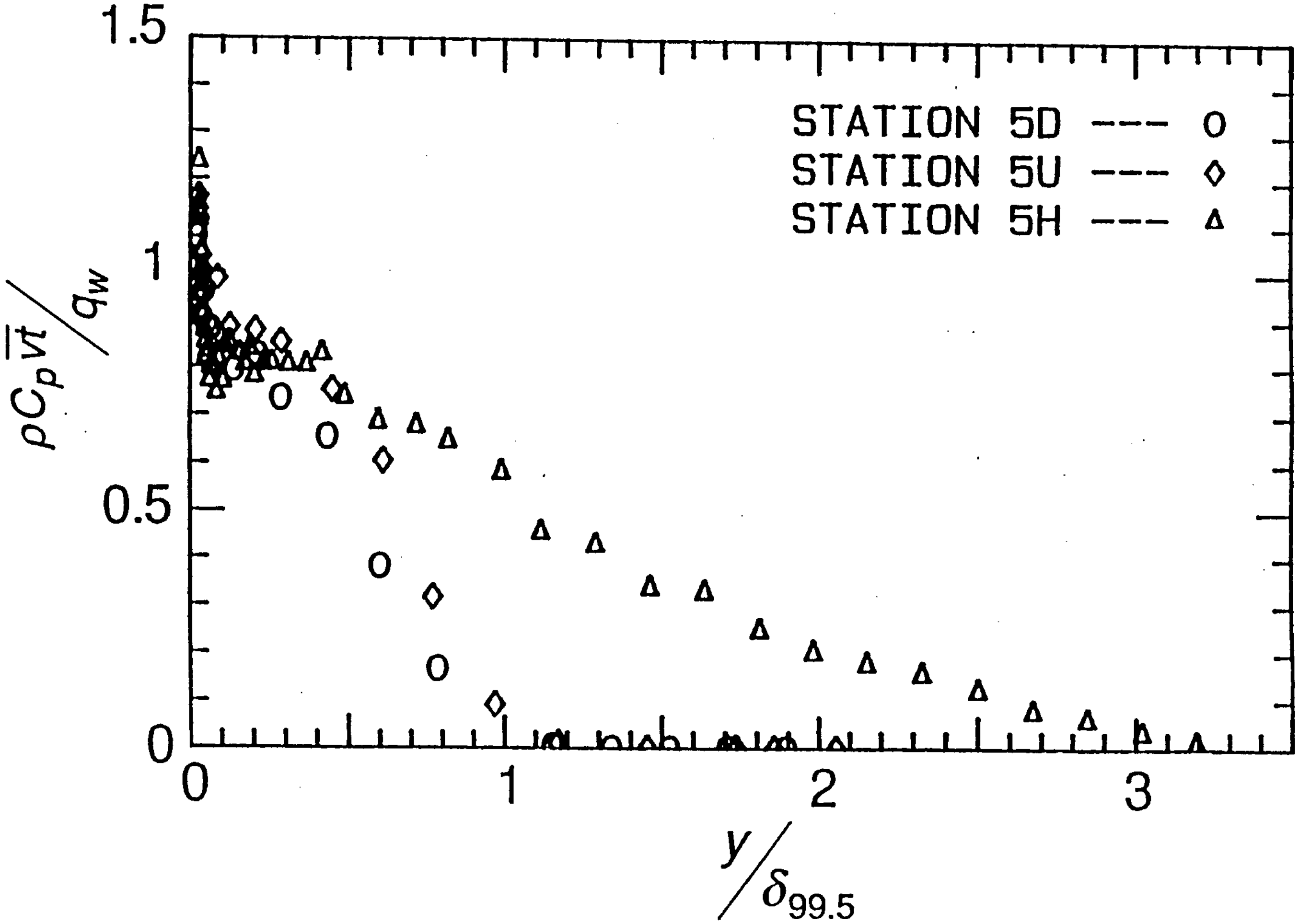

Fig. 19 Effect of TI on Cross-stream Turbulent Heat Fluxes over the Concave Wall. Station 5H--High TI; Station 5D and 5U--low TI.
D--Downwash, U--Upwash

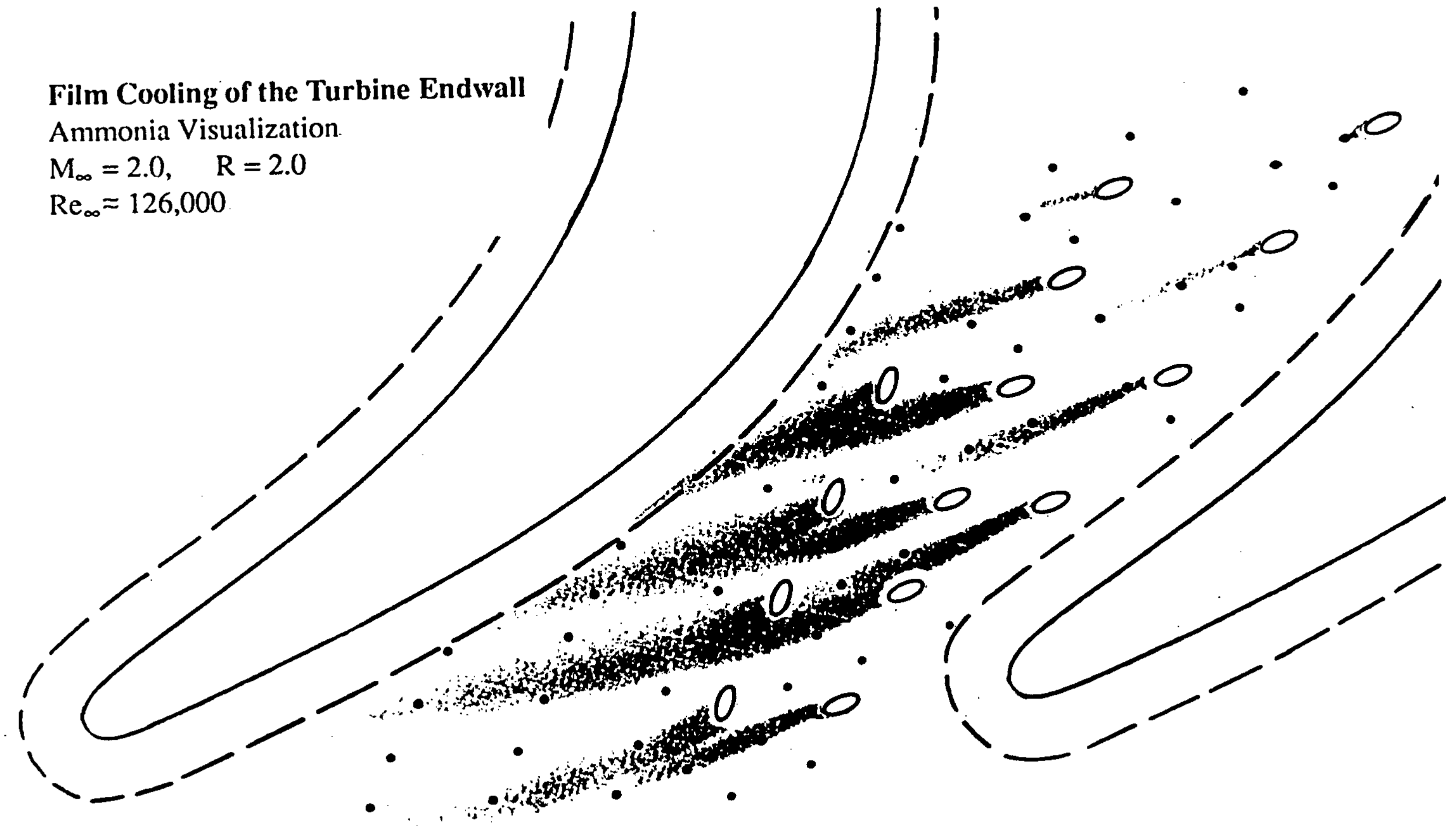

Fig. 20 Ammonia-Diazo visualization on the turbine endwall with film cooling ($M = 2.0$, $R = 2.0$, and $Re_\infty = 126,000$).

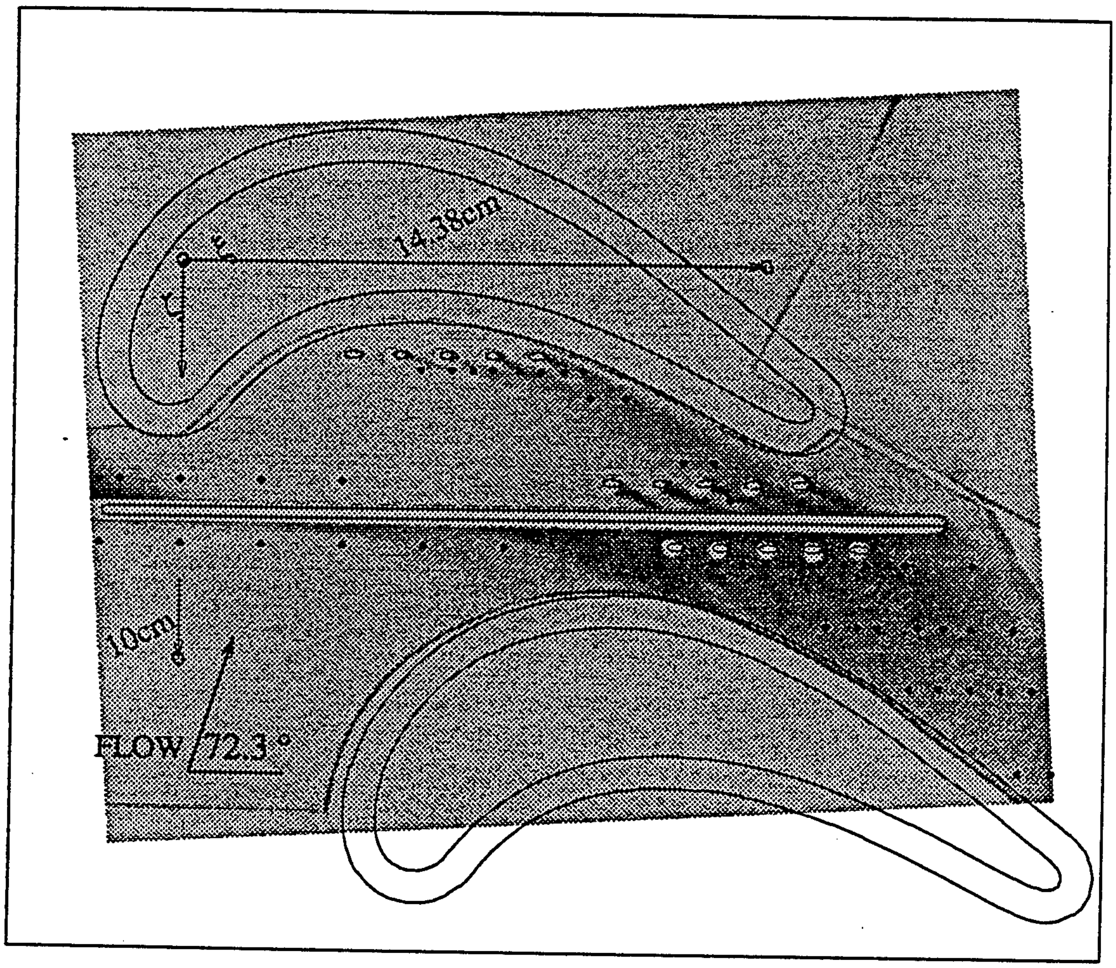

Fig. 21 Ammonia-Diazo visualization on the turbine endwall with injection through holes and a slot, (M_{hole} = 2.0, M_{slot} = 0.12, and R = 1.5).

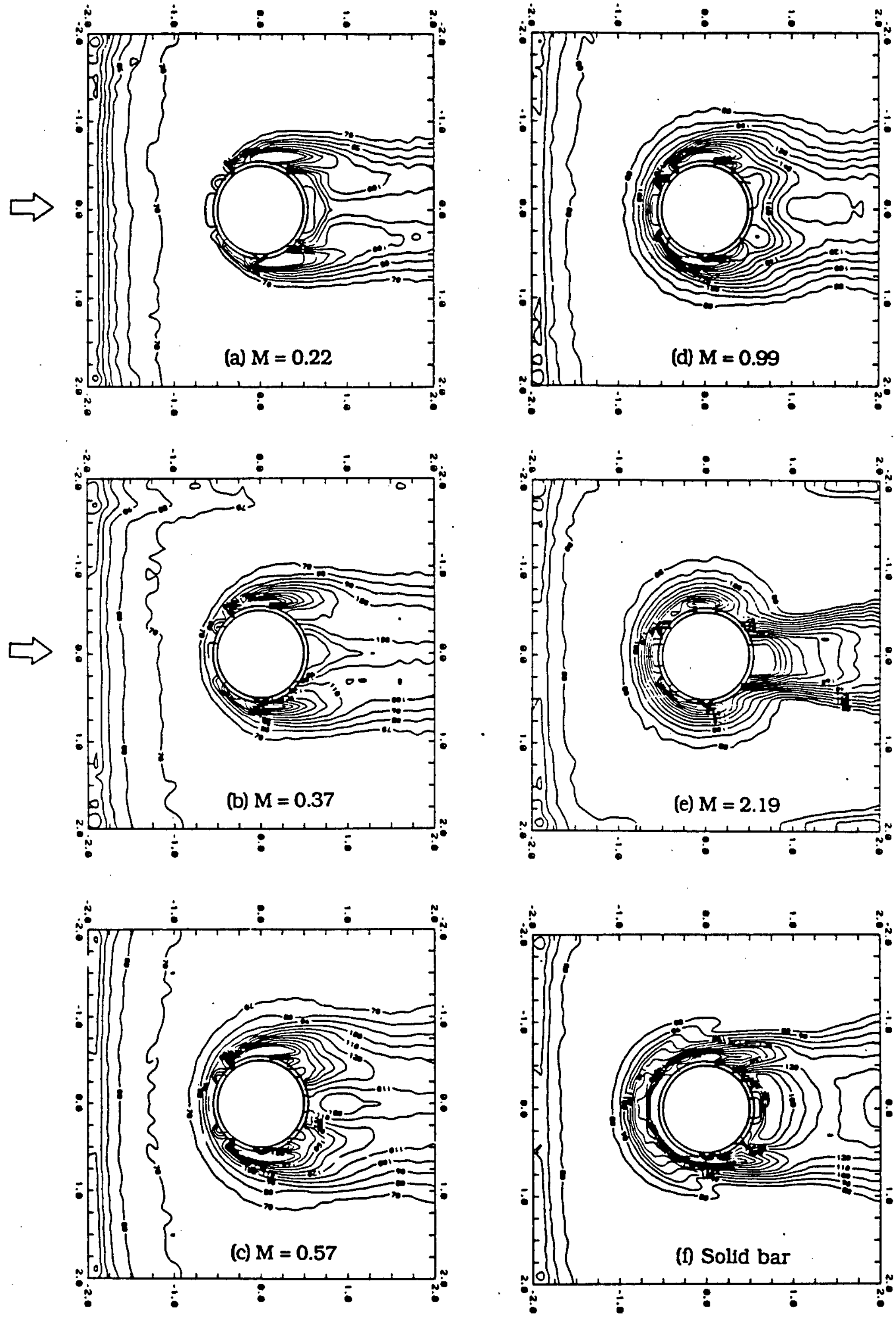

Fig. 22 Sherwood number contours for single hole injections.

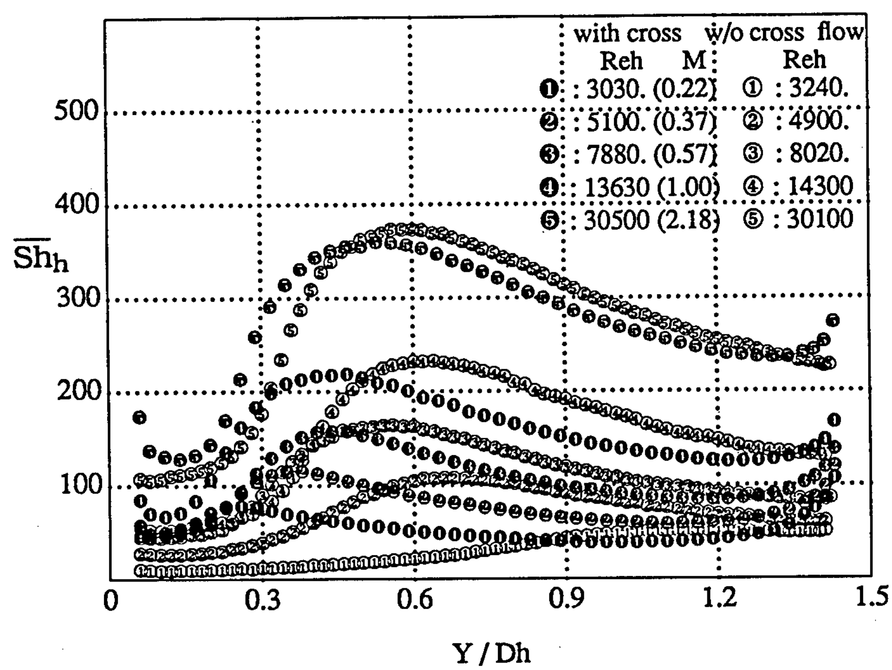

Fig. 23 Comparison of $\overline{Sh}_h$ with and without cross-flow (single hole).

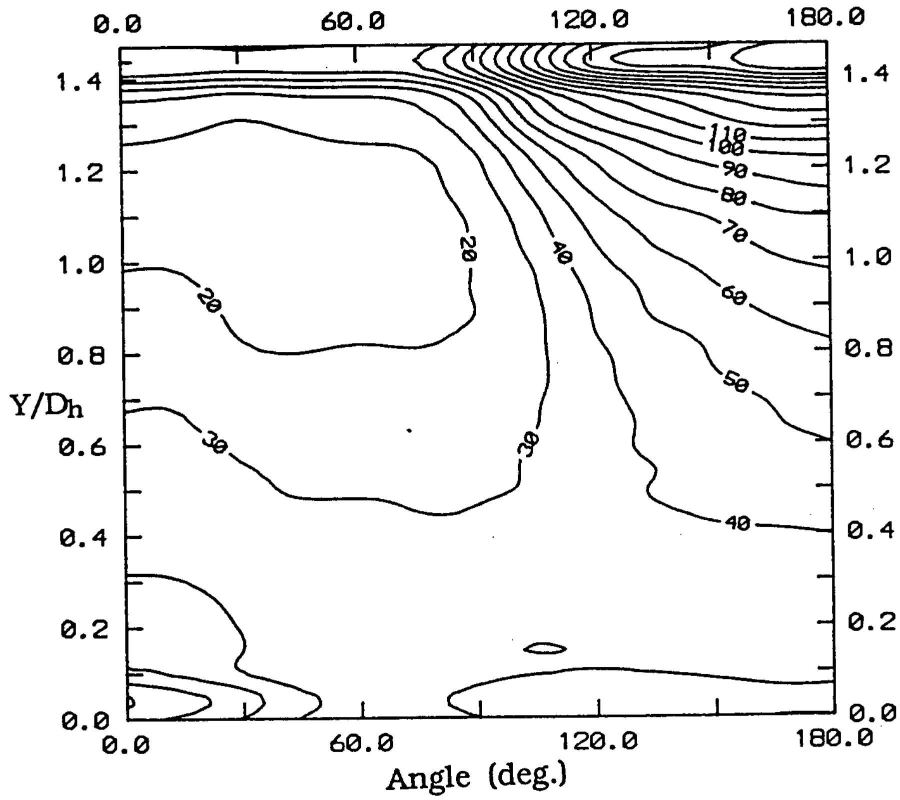

Fig. 24 Local Sh contour at $Re_h = 0$ and $M = 0$ (no injection).

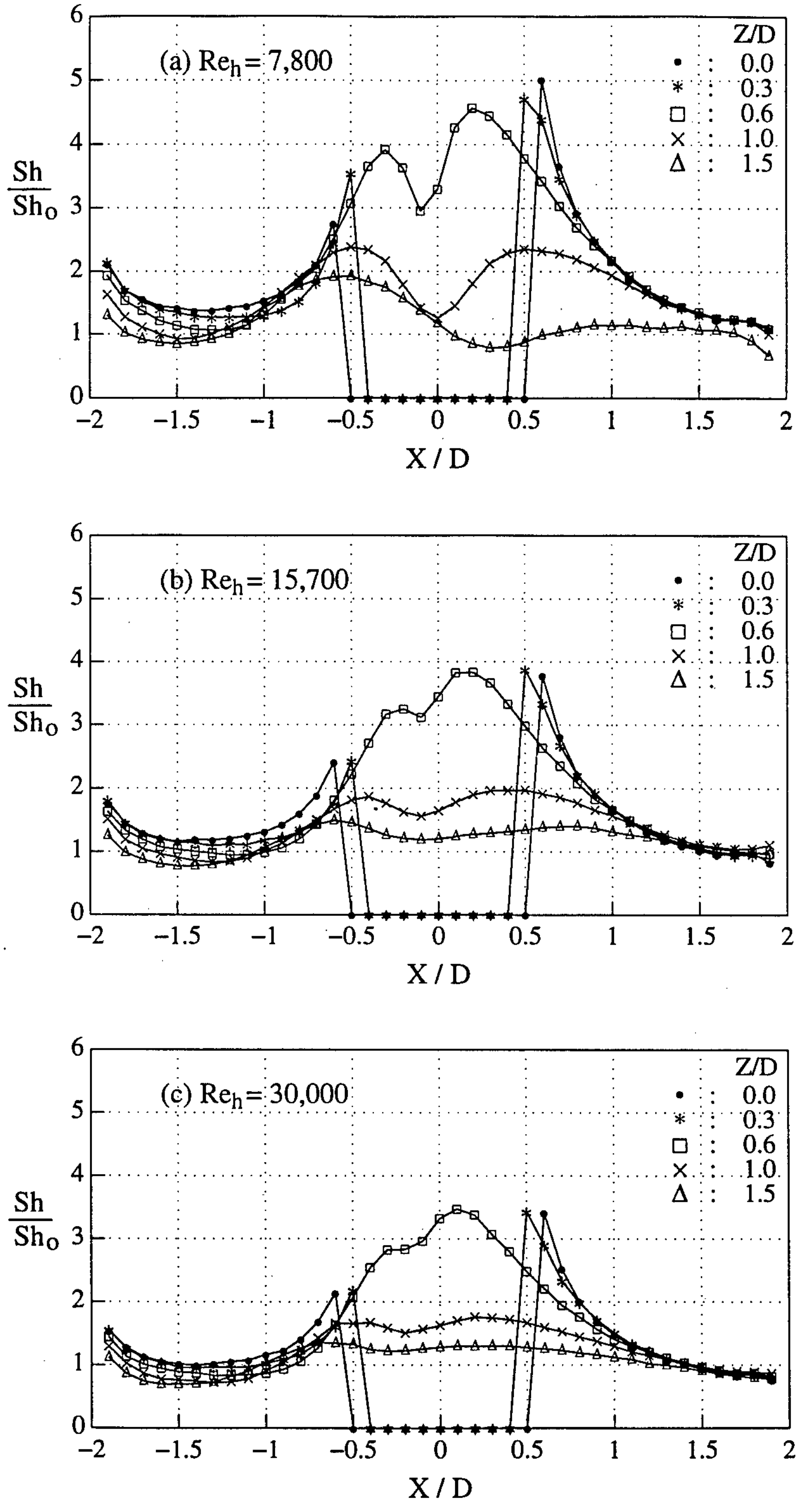

Fig. 25 Normalized Sh on plenum wall with one open hole.

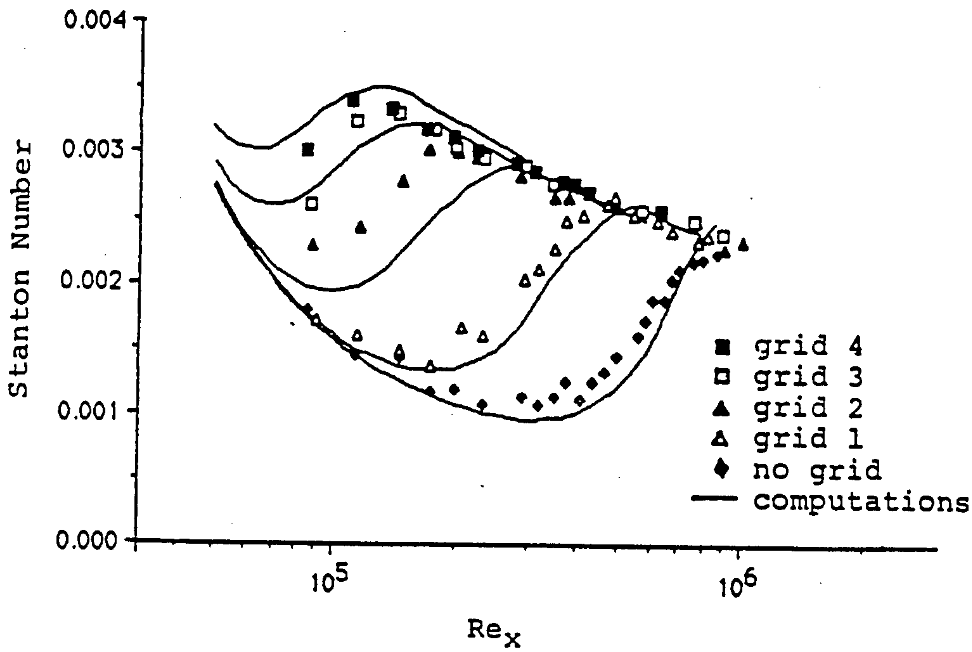

Fig. 26 Heat transfer during transition with zero pressure gradient and various free-stream turbulence levels (from Schmidt and Patankar, 1991b)

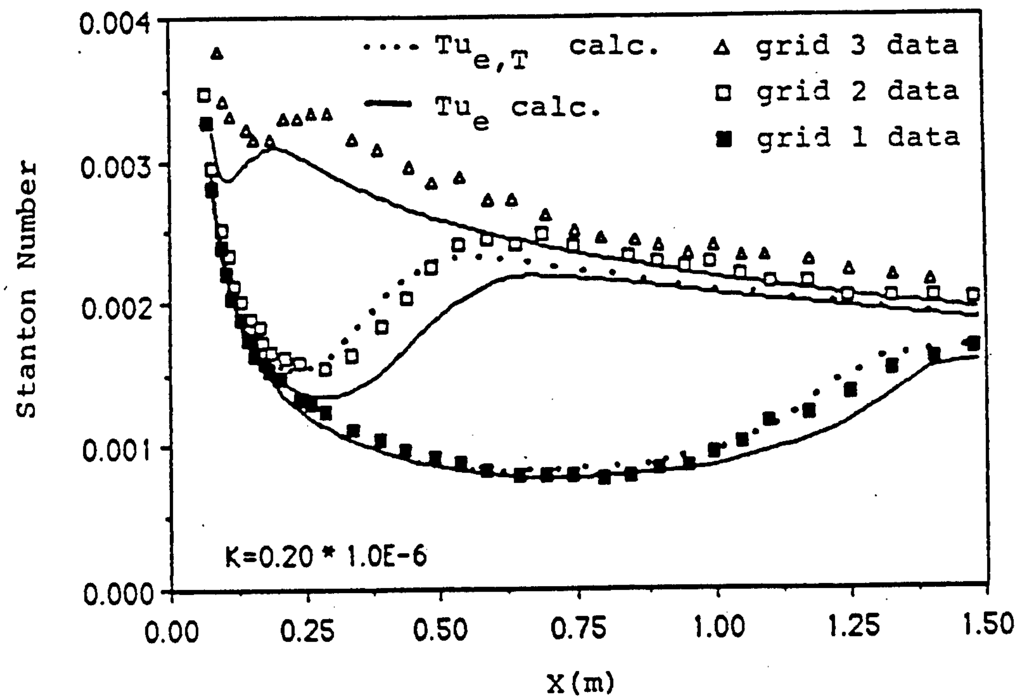

Fig. 27 Heat transfer during transition for an accelerating boundary layer and various free-stream turbulence levels (from Schmidt and Patankar, 1991b)

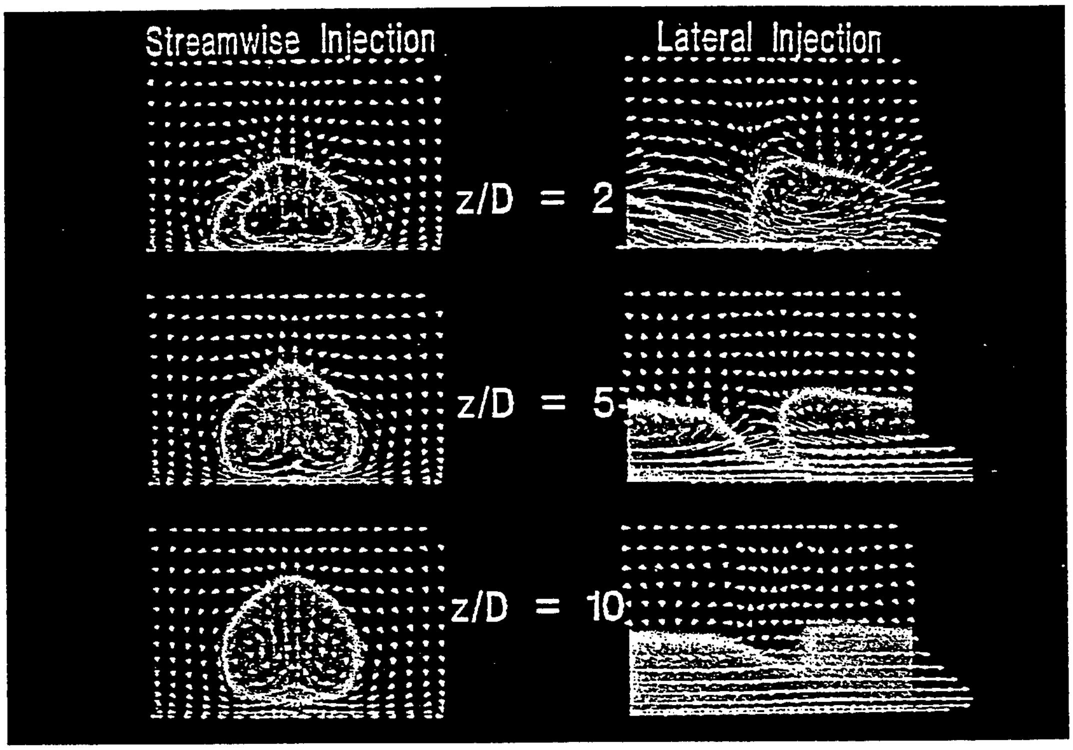

Fig. 28 Secondary flow patterns for streamwise and lateral injection (from Sathyamurthy and Patankar, 1990)

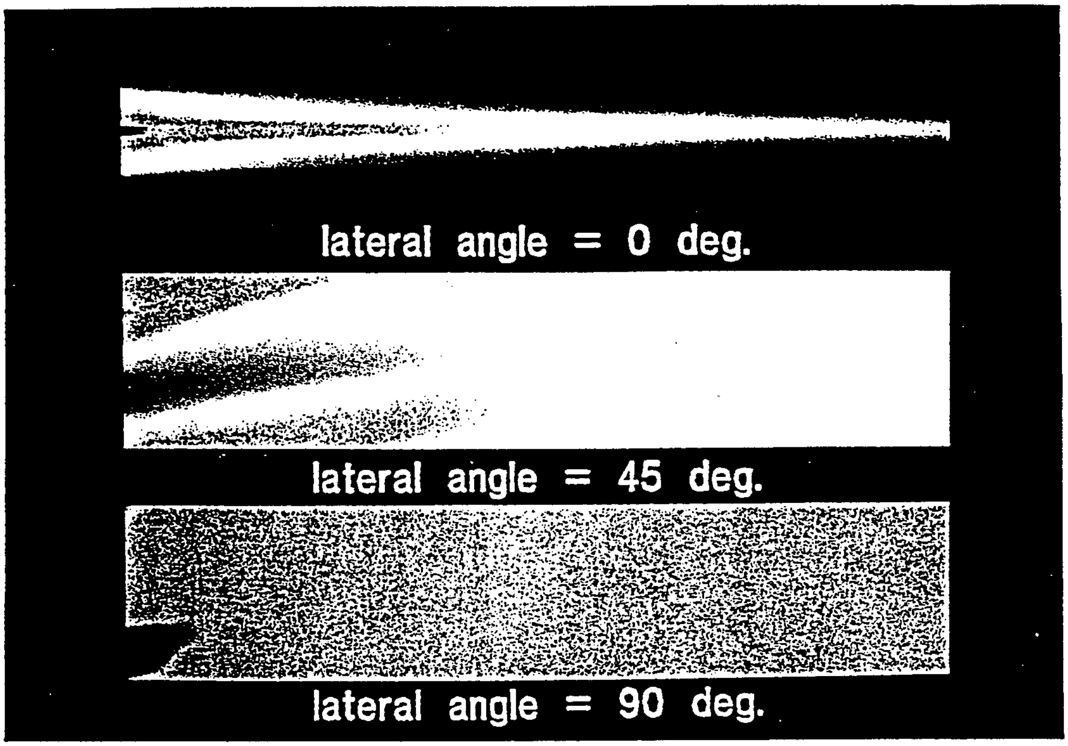

Fig. 29 Temperature distribution on the blade surface for different angles of lateral injection (from Sathyamurthy and Patankar, 1990)

Film cooling --- Streamwise injection

Isotropic turbulence model

Anisotropic turbulence model

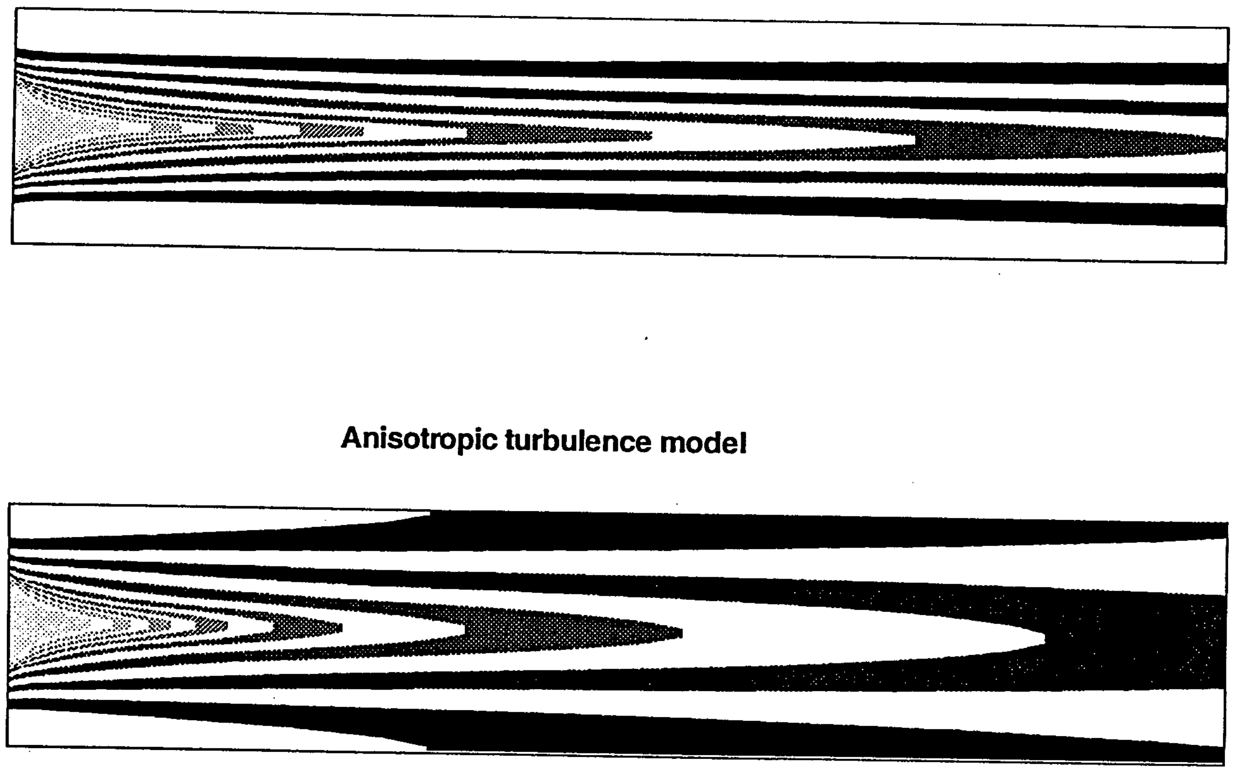

Fig. 30 Cooling effectiveness distributions predicted by the isotropic and anisotropic turbulence models
(from Sathyamurthy and Patankar, 1992)

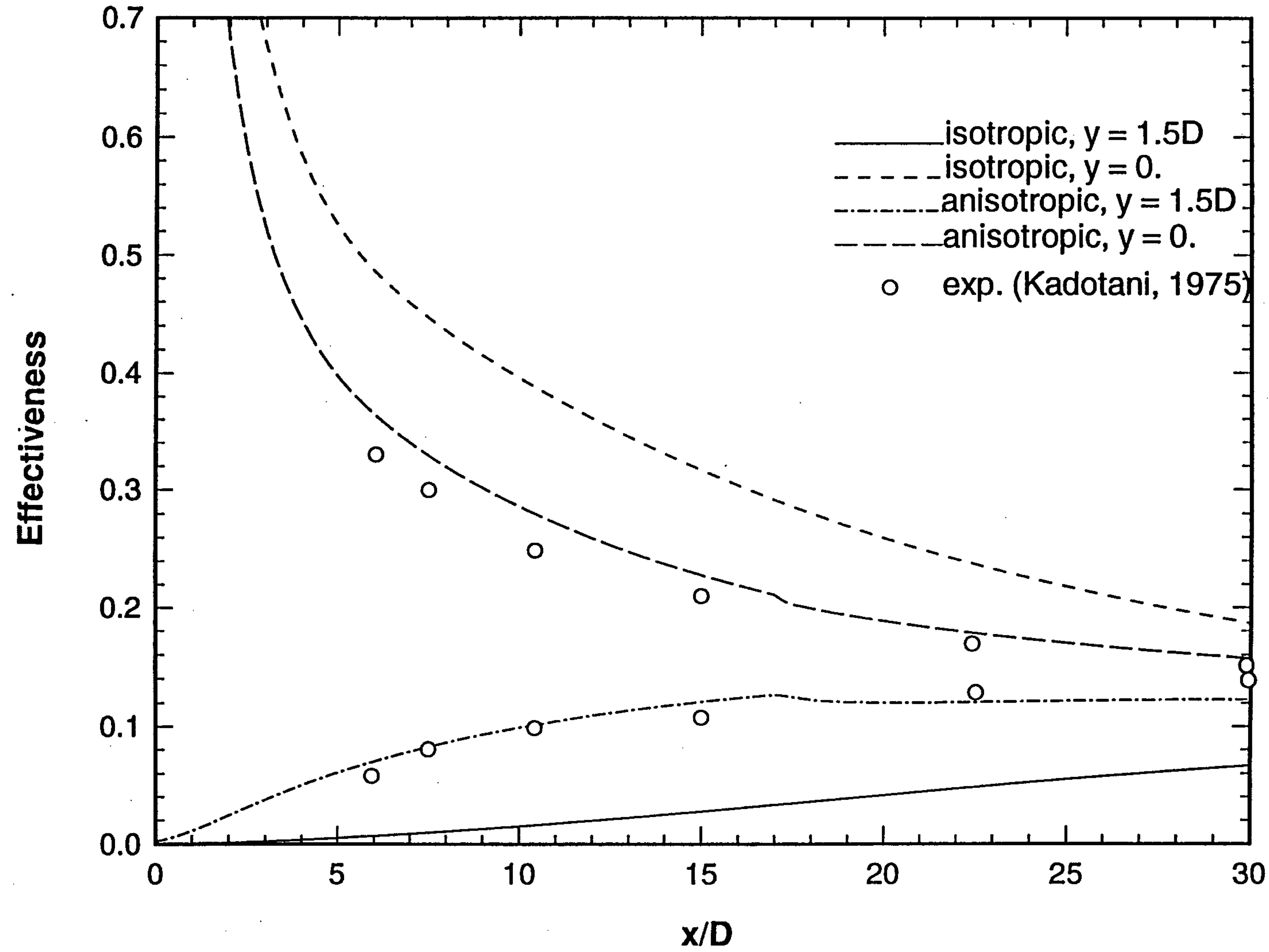

Fig. 31 Comparison of measured and predicted values of film-cooling effectiveness (from Sathyamurthy and Patankar, 1992)

Appendix A. Recent Publications on Gas Turbine Heat Transfer from the Heat Transfer Laboratory

Chen, P. H.., and Goldstein, R. J., 1992, "Convective Transport Phenomena on the Suction Surface of a Turbine Blade Including the Influence of Secondary Flows near the Endwall," *J. Turbomachinery*, Vol. 114, 776-787.

Chen, S. B., Goldstein, R. J., and Jabbari, M.Y., 1994, "Effect of Fin Shape on Fluid Flow and Heat Transfer Performance of Staggered Short Pin Fin Array," 10th Int. H. T. Conference, Paper No. EC4.

Cho, H. H. and Goldstein, R. J., 1993, "Heat (Mass) Transfer and Film Cooling Effectiveness with Injection Through Discrete Holes Part 1: Inside Holes and on the Back Surface," by ASME Paper No. 93-WA/HT-58; to appear in the J. Turbomachinery, 1995.

Cho, H. H. and Goldstein, R. J., 1993, "Heat (Mass) Transfer and Film Cooling Effectiveness with Injection Through Discrete Holes Part 2: On the Exposed Surface," by ASME Paper No. 93-WA/HT-59; to appear in the J. Turbomachinery, 1995.

Cho, H. H. and Goldstein, R. J., 1994, "An Improved Low-Reynolds-Number k-ε Turbulence Model for Recirculating Flows," Int J. Heat Mass Transfer, Vol. 37, pp. 1495-1508.

Cho, H.H., Jabbari, M.Y., and Goldstein, R.J., 1994, "Mass Transfer with Flow Trough an Array of Rectangular Cylinders," *J. Heat Transfer*, Vol. 116, pp. 904-911.

Cho, H. H. and Goldstein, R. J., 1995, "Total-Coverage Discrete Hole Wall Cooling," to appear in IGTI Conf., Houston, 1995.

Chung, J. T. and Simon, T. W.,1990, "Three-Dimensional Flow near the Blade/Endwall Junction of a Gas Turbine: Visualization in a Large-Scale Cascade Simulator," ASME Paper #90-WA/HT-4, Presented at the 1990 ASME Winter Annual Meeting, Dallas, Texas.

Chung, J. T. and Simon, T. W.,1991, "Three-Dimensional Flow near the Blade/Endwall Junction of a Gas Turbine: Application of a Boundary Layer Fence," ASME Paper #91-GT-45, presented at the International Gas Turbine and Aeroengine Congress and Exposition Orlando, Florida.

Chung, J. T. and Simon, T. W.,1993, "Effectiveness of the Gas Turbine Endwall Fences in Secondary Flow Control at Elevated Freestream Turbulence Levels," ASME Paper, 93-GT-51, presented at the International Gas Turbine and Aeroengine Congress and Exposition Cincinnati, Ohio.

Chyu, M.K. and Goldstein, R.J., 1991, "Influence of an Array of Wall Mounted Cylinders on the Mass Transfer from a Flat Plate," *Int. J. Heat Mass Transfer*, Vol. 34, No. 9, pp. 2175-2186.

Eckert, E.R.G., 1992, "Similarity Analysis of Model Experiments for Film Cooling to Gas Turbines," Wärme und Stoffübertragung, Vol. 27, pp. 217-223.

Eckert, E.R.G. and Cho, H.H., 1994, "Transition from Transpiration to Film Cooling," International Journal of Heat and Mass Transfer, Vol. 37 (S. 1), pp. 3-8.

Goldstein, R.J., Karni, J, and Zhu, Y., 1990, "Effect of Boundary Conditions on Mass Transfer Near the Base of a Cylinder in Crossflow," *J. Heat Transfer*, Vol. 112 (2), pp. 501-504.

Goldstein, R.J., Yoo, S.Y., and Chung, M.K., 1990, "Convective Mass Transfer from a Square Cylinder and Its Base Plate," *Int. J. Heat Mass Transfer* , Vol. 33, No. 1, pp. 9-18.

Goldstein, R. J., Sobolik, K. A., and Seol, W. S., 1990, "Effect of entrainment on the heat transfer to a heated circular air jet impinging on a flat surface," *J. Heat Transfer*, Vol. 112, No. 3, pp. 608-611.

Goldstein, R. J. and Seol, W. S., 1991, "Heat transfer to a row of impinging circular air jets including the effect of entrainment," *Int. J. Heat Mass Transfer*, Vol. 34, pp. 2133-2147.

Goldstein, R. J., 1992,"Heat Transfer Processes in High Temperature Gas Turbines," The 24th Israel Conference on Mechanical Engineering, pp. 1-4.

Goldstein, R. J., Jabbari, M. Y., and Brekke, J. P., 1992, "The Near-Corner Mass Transfer Associated with Turbulent Flow in a Square Duct", Warme und Stoffubertragung, Vol. 27, pp. 265-272.

Goldstein, R. J. and Cho, H. H., 1993 "A Review of Mass (Heat) Transfer Measurements Using Naphthalene Sublimation," Proceedings of the 3rd World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, M. D. Kelleher et al., Vol. 1, pp. 21-40, 1993; to appear in Journal of Experimental Science, 1995.

Goldstein, R. J., Wang, H. P.., and Jabbari, M. Y., 1994, "The Influence of Boundary Disturbance and Secondary Flows near the Endwall on Convective Transport from a Turbine blade," ASME paper, 94-GT-165.

Goldstein, R. J., Cho, H. H., and Jabbari, M. Y., 1994, "Effect of Plenum Cross-Flow on Heat (Mass) Transfer Near and Within the Entrance of Film Cooling Holes," ASME HTD-Vol. 300, pp. 1-14.

Goldstein, R.J., Jabbari, M.Y., and Chen, S.B., 1994, "Convective Mass Transfer and Pressure Loss Characteristics of Staggered Short Pin-Fin Arrays," *Int. J. Heat Mass Transfer* , Vol. 37 (Supp. 1), pp. 149-160.

Hain, R.C., Wang, H.P., Chen, P.H., and Goldstein, R.J., 1991, "A Microcomputer-Controlled Data Acquisition System for Naphthalene Sublimation Measurement," *Proc. of the 11th ABCM Mech. Eng. Conf.*, Sao Paulo, Brazil.

Jabbari, M. J., Goldstein, R. J., Marston, K. C., and Eckert, E. R. G., 1992, "Three Dimensional Flow at the Junction between a Turbine Blade and Endwall," *Warme- und Stoffubertragung*, Vol. 27, 51-59.

Jabbari, M. J. and Goldstein, R. J., 1992, "Visualization of Flow in the Endwall Region of a Turbine Cascade," Atlas of Visualization, Vol. 1, pp. 113-123.

Jabbari, M. Y., Marston, K. C., Eckert, E. R. G., and Goldstein, R. J., 1994, "Film Cooling Of The Gas Turbine Endwall With Discrete-Hole Injection", ASME Paper 94-GT-67.

Jabbari, M. J. and Goldstein, R. J., 1994, "Film Cooling, Mass Transfer, and Flow at the Base of a Turbine Blade," J. Engrg. Physic (in Russian), Vol. 65(3), pp. 350-355.

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Kestoras, M. D. and Simon, T. W., 1992, " Hydrodynamic and Thermal Measurements in a Turbulent Boundary Layer Recovering from Concave Curvature," ASME Journal of Turbomachinery, Vol.114, No. 4, PP. 891-898, 1992.

Kestoras, M. D. and Simon, T. W., 1993, "Combined Effects of Concave Curvature and High Free-Stream Turbulence Intensity on Boundary Layer Heat and Momentum Transport," ASME Paper #93-WA/HT-56, 1993 ASME Winter Annual Meeting, New Orleans, LA (1993); also to be published in the ASME Journal of Turbomachinery, 1994.

Kestoras, M. D. and Simon, T. W., 1993, "Effect of Free-Stream Turbulence Intensity on a Boundary Layer Recovering from Concave Curvature Effects," #93-GT-25, 1993, International Gas Turbine Conference, Cincinnati, Ohio.

Kestoras, M. D. and Simon, T. W., 1994, "Turbulence Measurement in a Heated, Concave Boundary Layer under High Free-stream Turbulence Conditions," ASME #94-GT-037, 1994, International Gas Turbine Conference, Hague, Netherlands.

Kestoras, M. D. and Simon, T. W., 1994, "Turbulent Heat and Momentum Transport Measurements: The Effect of Introduction and Removal of Concave Curvature," In Effects of Organized Vortex Motion on Heat and Mass Transfer, Proceedings of EUROMECH Colloquium 327, Presented in Kiev, Ukraine, August, 25-27, 1994.

Kestoras, M. D. and Simon, T. W., 1995, "Response of a Boundary Layer to Removal of Concave Curvature Under High Free-Stream Turbulence Condition: Turbulent Heat and Momentum Transport Measurement," ASME 1995 International Gas Turbine Conference, Houston, Texas.

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Kim, J., Simon, T. W. and M. Kestoras, 1995, "Fluid Mechanics and Heat Transfer Measurements in Transitional Boundary Layers Conditionally Sampled on Intermittency," to be in J. Turbomachinery.

Rask, R.B., Goldstein, R.J., and Jabbari, M.Y., 1990, "Flow and Mass Transfer in a Curved Wall Jet," 9th Int. H. T. Conf., Vol. 5, pp. 377-382.

Russ, S. and Simon, T. W., 1991, "On the Rotating Slanted, Hot-wire Technique," Experiments in Fluids, Vol. 12, pp. 76-80.

Sathyamurthy, P. S., and Patankar, S. V., 1992, "Film Cooling Studies Using a Three-Dimensional Parabolic Procedure," Minnesota Supercomputer Institute Research Report UMSI 92/144.

Sathyamurthy, P. and Patankar, S. V., 1990, "Prediction of Film Cooling with Lateral Injection," Heat Transfer in Turbulent Flows, ASME-HTD, Vol. 138, pp. 61-70.

Schmidt, R. and Patankar, S. V., 1991a, "Simulating Boundary Layer Transition with Low-Reynolds-Number k-ε Turbulence Models: Part 1 - An Evaluation of Prediction Characteristics," Journal of Turbomachinery, Vol. 113, pp. 10 - 17.

Schmidt, R. and Patankar, S. V., 1991b, "Simulating Boundary Layer Transition with Low-Reynolds-Number k-ε Turbulence Models: Part 2 - An Approach to Improving the Predictions," Journal of Turbomachinery, Vol. 113, pp. 18 - 26.

Schneider and Goldstein, R.J., 1994, "Laser Doppler Measurement of Turbulence Parameters in a Two-Dimensional Plane Wall Jet," *Physics of Fluids* , Vol. 6 (9), pp. 3116-3129.

Schwarz, S. G. and Goldstein, R. J., 1989, "The Two Dimensional Behavior of Film Cooling Jets on Concave Surfaces," J. Turbomachinery, Vol. 111, pp. 124-130.

Schwarz, S. G., Goldstein, R. J. and E. R. G. Eckert, 1991, "The Influence of Curvature on Film Cooling Performance," J. of Turbomachinery, Vol. 113 (3), pp. 472-478.

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